(2)

HSD-TR-89-001

NOISE AND SONIC BOOM IMPACT TECHNOLOGY

Sonic Boom Damage to Conventional Structures

Jerald Haber
David Nakaki

BBN Systems and Technologies Corporation
21120 Vanowen Street
Canoga Park, CA 91303

February 1989

Final Report for Period August 1987 - August 1988

Approved for public release; distribution is unlimited.

Noise and Sonic Boom Impact Technology
Human Systems Division
Air Force Systems Command
Brooks Air Force Base, TX 78235-5000

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility nor any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise as in any manner construed, as licensing the holder, or any other person or corporation; or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

The Office of Public Affairs has reviewed this report and it is releasable to the National Technical Information Service (NTIS), where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

ROBERT C. KULL, JR., Capt, USAF
NSBIT Program Manager

FOR THE COMMANDER

MICHAEL G. MACNAUGHTON, COL, USAF
Deputy Commander Development & Acquisition

Please do not request copies of this report from the Human Systems Division. Copies may be obtained from DTIC. Address your request for additional copies to:

Defense Technical Information Center
Cameron Station
Alexandria VA 22301-6145

If your address has changed, if you wish to be removed from our mailing list, or if your organization no longer employs the addressee, please notify HSD/SORT, Brooks AFB TX 78235-5000, to help us maintain a current mailing list.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS: None

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE:

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): BBN Report 6829

5. MONITORING ORGANIZATION REPORT NUMBER(S): HSD-TR-89-001

6a. NAME OF PERFORMING ORGANIZATION: BBN Systems and Technologies Corporation

6b. OFFICE SYMBOL *(If applicable)*:

7a. NAME OF MONITORING ORGANIZATION: Human Systems Division, Noise and Sonic Boom Impact Technology (NSBIT) Program

6c. ADDRESS *(City, State, and ZIP Code)*: 21120 Vanowen Street, Canoga Park, CA 91303

7b. ADDRESS *(City, State, and ZIP Code)*: OL-AC HSD/YA NSBIT, Wright-Patterson AFB, OH 45433-6573

8a. NAME OF FUNDING / SPONSORING ORGANIZATION: Noise and Sonic Boom Impact Technology Program

8b. OFFICE SYMBOL *(If applicable)*: HSD/YA-NSBIT

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F33615-86-C-0530

8c. ADDRESS *(City, State, and ZIP Code)*: OL-AC HSD/YA-NSBIT, Wright-Patterson AFB, OH 45433-6573

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.
63723F	3037	02	02

11. TITLE *(Include Security Classification)*: Sonic Boom Damage to Conventional Structures

12. PERSONAL AUTHOR(S): Haber, Jerold M. and Nakaki, David

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM 7/13/87 TO 4/89

14. DATE OF REPORT *(Year, Month, Day)*:

15. PAGE COUNT: 296

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
12	05	

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*: Sonic booms, structural response model, structural effects from sonic booms, conventional structures, damage to windows, plaster and bric-a-brac.

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

United States Air Force supersonic aircraft operations generate sonic booms which may effect existing structures. Typical effects of the sonic boom range from a mild nuisance to damage to windows, plaster and bric-a-brac. A literature survey was performed to identify existing models, suitable for an environmental planner to use for assessing the impact of supersonic flights on conventional structures. A model developed by Hershey and Higgins was identified as the most nearly suitable model. As a result of an extensive sensitivity analysis of this model, a number of enhancements to the model were developed. Finally, the revised mosel was "packaged" to facilitate use by an environmental planner.

A comparison of the existing U.S. Air Force methodology and the mean damage estimates produced by the new approach shows that the existing method <u>usually</u> produces higher loss estimates, although sometimes the loss estimates are comparable. The new method offers the advantage of quantifying the degree of conservatism in damage estimates and extending it from window panes to include other vulnerable materials.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: Geral Long, Lt. Col. USAF

22b. TELEPHONE *(Include Area Code)*: (513) 255-8416/8417

22c. OFFICE SYMBOL: HSD/YA-NSBIT

DD Form 1473, JUN 86 — *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

ACKNOWLEDGMENTS

A number of people contributed to the study which resulted in this technical report. We wish to acknowledge the work of Dr. Craig Taylor and Mr. Vijay Kopparam during the review of the field test data and existing mathematical models for assessing structural damage. Dr. John Wiggins provided his assessment of the state-of-the-art with regard to cumulative damage assessment based upon his personal experience in sonic boom damage research. Dr. David R. Webb provided a critical review of the authors' efforts, drawing upon his experience within the British Royal Aircraft Establishment. Mr. Andrew Kugler and Dr. William J. Galloway provided valuable direction regarding the environment in which the USAF planner using the results of this study must operate.

The technical review and encouragement of Mr. P.J. Gavankar of the Engineering Services Center at Tyndall AFB is gratefully acknowledged.

EXECUTIVE SUMMARY

At present, the impact of U.S. Air Force supersonic operations on structures is estimated as the number of windows which will be broken. This assessment involves counting the number of windows in an area, determining the peak overpressures to which they will be subjected, and evaluating a simple formula. Damage to materials other than windows is not addressed. An alternative model was developed under this task. In comparison to the new model, the window damage estimates produced by the old model tend to be conservative; they are, however, not uniformly so. Relative to the new model, the existing models estimates range from an underestimation by less than a factor of two to an overestimation of damage by several orders of magnitude.

A literature review was performed to identify existing candidate sonic boom damage models. Nineteen candidate models were considered. From this group of models, one (Hershey and Higgins) was selected as a baseline for the Noise and Sonic Boom Impact Technologiy (NSBIT) conventional structures damage model. This model was selected because the input requirements were reasonably compatible with the type of data an environmental planner has available to him, the output was in a form suitable for use by a planner, and the form of the model was sufficiently flexible to accommodate model refinements and extensions.

Extensive review and sensitivity analyses were performed of the baseline model to identify strengths and weaknesses of the model and to establish the necessary model enhancements. The sensitivity analysis addressed not only the parameters explicitly included in the model, but also the underlying factors upon which they depend. In some instances, this extended as far as the description of the "structural" element at risk.

The model was improved by changing the statistical framework, improving the structural response models, and extending the model to distinguish the response to different loading waveforms (i.e., the effects of wave shape and duration).

The enhanced model was then "packaged" to accommodate use by the planner. The enhanced model allows the planner to characterize the structural environment in terms of standard planning categories (e.g., single family dwellings, multi-family dwellings with 15 units, etc.). The model translates these categories into estimates of the number of vulnerable "structural" elements of each of several vulnerability categories. This approach is appropriate because the vulnerability of the structural elements is "usually" a good first order predictor of damage independent of information regarding the building in which they are included. Moreover, when the particular structure does contribute significantly to the vulnerability of an element, a more detailed characterization of the building than is typically available to an environmental planner is needed for this assessment. The exposure information is then combined with the sonic boom hazard distribution to estimate the damage which will result from supersonic operations.

Another aspect of this study was the cumulative damage which results from supersonic overflight. Cumulative damage is the damage from repeated booms in excess of the net sum of the damage from individual booms. A literature review was performed and tentative findings in that literature were evaluated to assess their significance.

From the literature review, the following conclusions are drawn:

1. There are no completely satisfactory models for predicting cumulative damage as a function of boom strength and the number of boom exposures.

2. The evidence for a cumulative damage effect in glass and plaster is weak. For glass, the test results do not show that the glass itself is substantially affected by repeated booms. For plaster, the test results indicate that there may possibly be a cumulative damage effect at higher overpressures.

3. There is evidence for a cumulative damage threshold overpressure. That is, if there is a cumulative damage effect, it is associated with some minimum nominal overpressure.

4. The influences of naturally occurring forces due to the environment or from human activity over time can cause damage which is on the same order as that due to sonic booms. At low overpressures, the environmental factors are more severe than those from the sonic booms.

5. The fatigue behavior of glass and plaster is not well understood. In general, brittle materials like glass and plaster would not be expected to possess fatigue behavior similar to metallic materials. The sonic boom fatigue testing has concentrated on determining the behavior of the material by itself. However, there is evidence that the damage from repeated booms may be more strongly influenced by stress raisers where the glass or plaster is supported. In windows, these stress raisers appear as nails holding the window molding together, glazing points, or any other object which may abrade or impact the glass. For plaster elements, nails are most often used to attach lath to

the supporting structural members. These nails can act to concentrate local stresses in the plaster during the dynamic response.

From the investigation using the glass and plaster fatigue models to compare the damage probabilities for repeated and single booms, the following are the key findings:

1. Using an estimate of 200 sonic boom exposures per year and an expected lifetime of a building of 50 years, the material capacity reductions conservatively estimated for a lifetime exposure to sonic booms were not exceptionally large: on the order of 20 to 25%.

2. If it is assumed that those fatigue relations are valid, the damage estimations for the lifetime exposure are within a one standard deviation uncertainty of the single event damage predictions.

3. Sound, defendable cumulative damage models for glass and plaster cannot be recommended without further investigation.

TABLE OF CONTENTS

SECTION		PAGE
1	INTRODUCTION	1
	1.1 Objective	1
	1.2 Background	2
	1.3 Organization of Report	9
2	LITERATURE SEARCH	11
3	THE BASELINE MODEL	27
	3.1 Introduction	27
	3.2 Development of Probability Distributions	29
	3.3 Confidence Bounds for Probability Estimates	33
	3.4 General Observations	33
	3.5 Extensions to Other Building Elements	34
	3.5.1 Plaster	34
	3.5.2 Bric-a-brac	36
	3.5.3 Brick	37
4	EVALUATION OF THE BASELINE MODEL	41
	4.1 Introduction	41
	4.2 Window Damage Model	43
	4.3 Plaster Damage	74
	4.4 Bric-a-brac Damage	83
	4.5 Brick Damage	83
	4.6 Alternative Probability Distribution	83
	4.7 Summary of Model Enhancements	90
5	CUMULATIVE DAMAGE	95
	5.1 Introduction	95
	5.2 Review of the Cumulative Damage Literature	95
	5.2.1 Field Tests and Damage Surveys	96
	5.2.2 Laboratory Tests	99
	5.3 Evaluation of the Significance of Cumulative Damage	105
	5.3.1 Comparison with the Single Event	106
	5.3.1.1 Windows	107
	5.3.1.2 Plaster Elements	116
	5.3.2 Comparison with Environmental Effects	125
6	ASAN MODEL FOR DAMAGE TO CONVENTIONAL STRUCTURES	133
	6.1 Introduction	133
	6.2 ASAN Categories of Conventional Structures	134
	6.2.1 Window Categories	136
	6.2.2 Plaster Element Categories	140

TABLE OF CONTENTS (CONTINUED)

SECTION		PAGE
	6.2.3 Relationship of Structural Categories and Elements	145
	6.3 ASAN Damage Assessment Logic.	154
	6.4 Damage Assessment Details	159
	6.4.1 Load Model	161
	6.4.2 Dynamic Amplification Factors.	165
	6.5 Provisions for Extensions of the Model. . . .	167
7	CONCLUSIONS AND RECOMMENDATIONS	169
	7.1 Conclusions	169
	7.2 Recommendations	174
REFERENCES		
APPENDIX A	SONIC BOOM DAMAGE MATRICES	
APPENDIX B	CONTRIBUTIONS TO DAF UNCERTAINTY	
APPENDIX C	THE EFFECTS OF SONIC BOOMS ON CONVENTIONAL STRUCTURES	
APPENDIX D	ASAN PROTOTYPE CONVENTIONAL STRUCTURES DAMAGE ASSESSMENT	

LIST OF FIGURES

FIGURE NUMBER		PAGE
1-1	Scenario for Comparison of Old and New Damage Assessment Approaches	5
4-1	Comparison of Basic Model and NASA Model for Ratio of Measured to Predicted Freefield Over Pressure	46
4-2	Comparison of Alternative Treatments of Variability in the Ratio of External to Freefield Over Pressure	48
4-3a	Typical Sonic Boom (N-wave) Form	52
4-3b	General Spiked N-Wave Form	53
4-4	Typical Focused Sonic Boom Wave Form	54
4-5	Variation of Maximum (DAF) of SDOF System Due to N-Wave	55
4-6	Sensitivity of N-Wave Dynamic Amplification (Magnification) Factor To Asymmetry for an Undamped System	56
4-7	Sensitivity of N-Wave Dynamic Amplification (Magnification) Factor To Rise Time for an Undamped System	57
4-8	Sensitivity of N-Wave Dynamic Amplification (Magnification) Factor To Spiked Waveform for an Undamped System	58
4-9	Maximum (DAF) of Undamped SDOF System Due to Focused Sonic Boom	59
4-10	Maximum (DAF) of SDOF System Due to Focused Sonic Boom	60
4-11	Variation of Maximum (DAF) of SDOF Due to Focused Sonic Boom	61
4-12	Sensitivity of Maximum (DAF) of SDOF System to Ratio of Amplitude of Peaks	63
4-13	Sensitivity of Maximum (DAF) of SDOF System to Width of First Peak	64

LIST OF FIGURES (CONTINUED)

FIGURE NUMBER PAGE

4-14 Sensitivity of Maximum (DAF) of SDOF System to Amplitude of Negative Peak 65

4-15 Sensitivity of Baseline Window Damage Probability Model to DAF Statistics 66

4-16 Sensitivity of Baseline Window Damage Probability Model to Wave Type & DAF 67

4-17 Sensitivity of Breakage Probability to the Strength Reduction Factor 70

4-18 Sensitivity of the Capacity of a Window to Load Duration. 71

4-19 Sensitivity of the Capacity of a Window to Load Duration (Over Pressure 5-10 psf). 72

4-20 Sensitivity of the Capacity of a Window to Load Duration (Over Pressure 10-20 psf) 73

4-21 Sensitivity of the Probability of Ceiling Plaster Cracking to Response Model (Over Pressure = 2-5 psf) 77

4-22 Sensitivity of the Probability of Ceiling Plaster Cracking to Response Model (Over Pressure = 5-10 psf) 78

4-23 Sensitivity of the Probability of Ceiling Plaster Cracking to Response Model (Over Pressure = 10-20 psf) 79

4-24 Sensitivity of the Probability of Wall Plaster Cracking to Response Model (Over Pressure 2-5 psf) 80

4-25 Sensitivity of the Probability of Wall Plaster Cracking to Response Model (Over Pressure 5-10 psf) 81

4-26 Sensitivity of the Probability of Wall Plaster Cracking to Response Model (Over Pressure 10-20 psf) 82

LIST OF FIGURES (CONTINUED)

FIGURE NUMBER		PAGE
4-27	Comparison of Beta and Lognormal Probability Distributions for Type-C Predamaged Window (Best Estimate)	88
4-28	Comparison of Beta and Lognormal Probability Distributions for Type-C Predamaged Window (Low Estimate)	89
5-1a	Example Window Breakage Probabilities for Single and Repeated N-Wave Sonic Booms (Over Pressure 2-30 psf)	112
5-1b	Example Window Breakage Probabilities for Single and Repeated N-Wave Sonic Booms. . .	113
5-2a	Example Window Breakage Probabilities for Single and Repeated Focused Sonic Booms (Over Pressure 2-30 psf)	114
5-2b	Example Window Breakage Probabilities for Single and Repeated Focused Sonic Booms (Over Pressure 1-6 psf)	115
5-3a	Plaster Ceiling Cracking Probabilities for Single and Repeated N-Wave Sonic Booms (Over Pressure 2-30 psf).	119
5-3b	Plaster Ceiling Cracking Probabilities for Single and Repeated N-Wave Sonic Booms (Over Pressure 1-5 psf)	120
5-4a	Plaster Ceiling Cracking Probabilities for Single and Repeated Focused Sonic Booms (Over Pressure 2-30 psf).	122
5-4b	Plaster Ceiling Cracking Probabilities for Single and Repeated Focused Sonic Booms (Over Pressure 1-5 psf)	123
5-5a	Wood Stud Plaster Wall Cracking Probabilities for Single and Repeated N-Wave Sonic Booms (Over Pressure 0-30 psf).	126
5-5b	Wood Stud Plaster Wall Cracking Probabilities for Single and Repeated N-Wave Sonic Booms (Over Pressure 2-10 psf).	127

LIST OF FIGURES (CONCLUDED)

FIGURE NUMBER	PAGE
5-6a Wood Stud Plaster Wall Cracking Probabilities for Single and Repeated Focused Sonic Booms (Over Pressure 2-30 psf).	128
5-6b Wood Stud Plaster Wall Cracking Probabilities for Single and Repeated Focused Sonic Booms (Over Pressure 1-6 psf)	129

LIST OF TABLES

TABLE NUMBER		PAGE
1-1	Window Inventory for the Example Scenario	6
1-2	Comparison of Predicted Number of Broken Windows For the F-15 Fighter Aircraft Example Scenario Using the Existing Air Force Method and the New Methodology	6
1-3	Comparison of Predicted Number of Broken Windows For the B1B Bomber Example Scenario Using the Existing Air Force Method and the New Methodology	7
1-4	Plaster Element Inventory for the Example Scenario	7
1-5	Predicted Number of Damaged Plaster Elements for the F-15 Fighter Aircraft Example Scenario Using the New Methodology	7
1-6	Predicted Number of Damaged Plaster Elements for the B1B Bomber Example Scenario Using the New Methodology	8
1-7	Predicted Number of Damaged Bric-a-brac Items for the F-15 Fighter Aircraft Example Scenario Using the New Methodology	8
1-8	Predicted Number of Damaged Bric-a-brac Items for the B1B Bomber Example Scenario Using the New Methodology	8
2-1	Failure Patterns in Conventional Buildings	12
2-2	Description of Available Models	17
2-3	Characteristics of Identified Models	23
3-1	Hershey/Higgins Model Parameters for Window Damage	32
3-2	Hershey/Higgins Model Parameters for Plaster Damage	36
3-3	Static Failure Pressures of Brick Walls	39
4-1	Modeled Limits of Random Variables	85

LIST OF TABLES (CONTINUED)

TABLE NUMBER		PAGE
4-2	"Threshold" Damage Pressures	86
5-1	Categories of Windows	108
5-2	Predicted Mean Breaking Pressures for the Example Window for Repeated Sonic Booms	109
5-3a	Statistics for the Window Example for N-Wave	110
5-3b	Statistics for the Window Example for Focused Waves	110
5-4	Predicted Mean Breaking Pressures for Plaster Ceilings for Repeated Sonic Booms	117
5-5a	Statistics for Plaster Ceilings for N-Waves	118
5-5b	Statistics for Plaster Ceilings for Focused Waves	118
5-6	Predicted Mean Breaking Pressures for Wood Stud Plaster Walls for Repeated Sonic Booms	121
5-7a	Statistics for Wood Stud Plaster Walls for N-Waves	124
5-7b	Statistics for Wood Stud Plaster Walls for Focused Waves	124
6-1	ASAN Structural Categories	135
6-2	Categories of Windows	137
6-3	Baseline Glass Breaking Pressure Statistics	138
6-4	Factors for Adjusting Breaking Pressures for Load Duration	139
6-5	Plaster Elements	142
6-6	Plaster Breaking Pressures	144
6-7	Mean and Variance Estimates for the Number of Windows by Window Category for Mobile Homes	145

LIST OF TABLES (CONTINUED)

TABLE NUMBER		PAGE
6-8	Mean and Variance Estimates for the Number of Elements by Element Category for Mobil Homes	146
6-9	Mean and Variance Estimates for the Number of Window by Window Category for Single Family Dwellings	146
6-10	Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Single Family Dwellings	147
6-11	Mean and Variance Estimates for the Number of Windows by Window Category for Multi-Family Dwellings	147
6-12	Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Multi-Family Dwellings	148
6-13	Mean and Variance Estimates for the Number of Windows by Window Category for Churches	148
6-14	Mean and Variance Estimates for the Number of Plaster elements by Element Category for Churches	149
6-15	Mean and Variance Estimates for the Number of Windows by Window Category for Hospitals	149
6-16	Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Hospitals	150
6-17	Mean and Variance Estimates for the Number of Windows by Window Category for Office Buildings	150
6-18	Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Office Buildings	151
6-19	Mean and Variance Estimates for the Number of Windows by Window Category for Commercial Establishments	151

LIST OF TABLES (CONCLUDED)

TABLE NUMBER		PAGE
6-20	Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Commercial Establishments	152
6-21	Mean and Variance Estimates for the Number of Windows by Window Category for Schools	152
6-22	Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Schools	153
6-23	Sonic Boom Reporting Intervals	155
6-23a	Duration Intervals	155
6-23b	Overpressure Intervals	156
6-24	Summary of ASAN Model Treatment of Variables	161
6-25	ASAN Model Statistics of P_f/P_o	163
6-26	ASAN Log (P_e/P_f) Statistics	164
7-1	Recommended Programs for Further Study	182

SONIC BOOM DAMAGE TO CONVENTIONAL STRUCTURES

1. INTRODUCTION

1.1 Objective

Public Law 96-588, the National Environmental Policy Act (NEPA) of 1969, requires the United States Air Force (USAF) to conduct environmental assessments of its flight activities. NEPA and other regulations apply not only to flight operations near air bases, but also to operations in about 350 Military Operating Areas (MOAs) and Restricted Areas (RAs), and along 400-odd Military Training Routes (MTRs), encompassing roughly a half million square miles of domestic airspace. Compliance with statutory and regulatory environmental requirements is not a simple task for the USAF; it poses technical and practical challenges in providing a complete assessment of the potential consequences of these operations and in responding to the public concerns about possible consequences.

Task 0008 of Contract F33615-86-C-0530 addresses these needs by establishing the types of conventional structures which are of interest to the environmental planner, identifying existing structural damage models which may be applied to sonic damage, selecting the best of these models and developing a database that will support these models with minimal input from an environmental planner. While the most common load levels expected from these supersonic operations are 2 pounds per square foot (psf) or less, the planner must be able to address loads up to 30 psf. The database and models are to be incorporated into an automated environmental planning aid called Assessment System for Aircraft Noise (ASAN), which is being developed as part of the Noise and Sonic Boom Impact Technology (NSBIT) program. This document presents the findings of this task, which includes currently available models, a proposed

damage model for ASAN, a prototype support database for the model, and recommendations for further research and development.

1.2 Background

An environmental planner must be able to address site-specific situations where aircraft operations may have an impact on structures. In a typical scenario, a planner may be confronted with a planned MOA or MTR covering an expanse of several hundred square miles that encompasses a wide range of structural types. The planner must be able to determine the impacts of overflights from tactical fighters and strategic bombers. The planner must be able to determine the effects of not only individual events, but also different numbers and types of sonic boom loads on a wide variety of structural systems. Once these effects have been determined, the planner should use the other factors impacting a structure, such as the natural elements and aging of materials, to determine the net impact of the operations.

At present a U.S. Air Force environmental planner charged with assessing the environmental effects of aircraft operations has no well-defined method for performing this assessment. While the U.S. Air Force has published a guideline for assisting the planner -- "Assessing Noise Impacts of Air Force Operations, Guidelines", (3) -- this document provides the planner with limited assistance. It assumes that the only property damage which may occur is glass breakage. Furthermore, it provides generalizations which assume that all MOAs have the same distributions of window types, sizes and strengths. Thus, a moderately knowledgeable critic of an existing environmental document is provided ample opportunity for criticism.

In a different operating environment the lack of complete guidelines might be overcome by the accumulation of "hands-on" experience by responsible personnel. In the U.S. Air Force, the typical planner does not have an opportunity to develop a personal knowledge base to supplement official guidelines so that he may reflect the characteristics of his areas of responsibility. The U.S. Air Force procedure of rotating assignments affords the planner little opportunity to develop experience to assist him in this task.

To address these needs, NSBIT has funded the development of a microcomputer based planning aid, the Assessment System for Aircraft Noise (ASAN). Key components of ASAN will include interface modules, calculation modules, and position papers. Interface modules allow a planner to characterize his problem in a nontechnical manner and prepare his inputs for evaluation. Calculation modules will assess the effects of proposed operations and generate numerical evaluations of anticipated damage levels. The position papers will provide a nontechnical synopsis of the technology which enabled the damage evaluations to be performed.

The calculation module developed for conventional structures allows the planner to describe the conventional structures within a planning area in terms of standard planning categories. The calculation module translates this information into an inventory of different types of bric-a-brac, windows, plaster walls, and ceilings. Development of an inventory of building elements is necessary for several reasons. At the level of detail available to the environmental analyst, it is not feasible to consider the structural response of individual buildings. Moreover, the characteristics of the building element are, typically, significantly more important than that of the building in which they are incorporated in attempting to predict damage. By comparing the strength of the elements to

the applied loads from the supersonic overflights on a probabilistic basis, means and variances of damage are generated.

As a preview of the capability of the new damage evaluation methodology, consider the example scenario shown in Figure 1-1. Two types of aircraft, an F-15 fighter aircraft and a B1B bomber, fly on the illustrated flight track generating the sonic boom overpressures and wave durations shown. The structures represented are included among the standard planning categories presented later in this report. The inventory of windows at each site are shown in Table 1-1. In the new methodology, windows are categorized according to their areas in square feet. Type A corresponds to areas between 0 and 2 ft^2 (.61 m^2), Type B corresponds to areas between 2 and 10 ft^2 (3.05 m^2), and Type C corresponds to areas between 10 and 50 ft^2 (15.24 m^2). Tables 1-2 and 1-3 present a comparison of the predicted number of broken panes using the traditional USAF method and the new methodology. For the new methodology, mean and mean plus one standard deviation damage predictions are shown. In all cases except for the mobile home park subjected to the B1B bomber sonic boom, the mean damage predictions using the new method are lower than those using the existing USAF method. It is important to notice that while the existing method produces damage estimates close to the new method in some cases, in other cases (for example, the mean window damage estimates for the ranch from the F-15 fighter aircraft overflight) the existing methodology is extremely conservative.

In addition to providing damage estimates for windows, the new methodology also can predict damage to plaster elements and bric-a-brac. Again, as a preview of the new method, consider the scenario of Figure 1-1, in which the inventory of plaster elements at each site is as shown in Table 1-4: the type A element corresponds to a plaster ceiling of wood frame

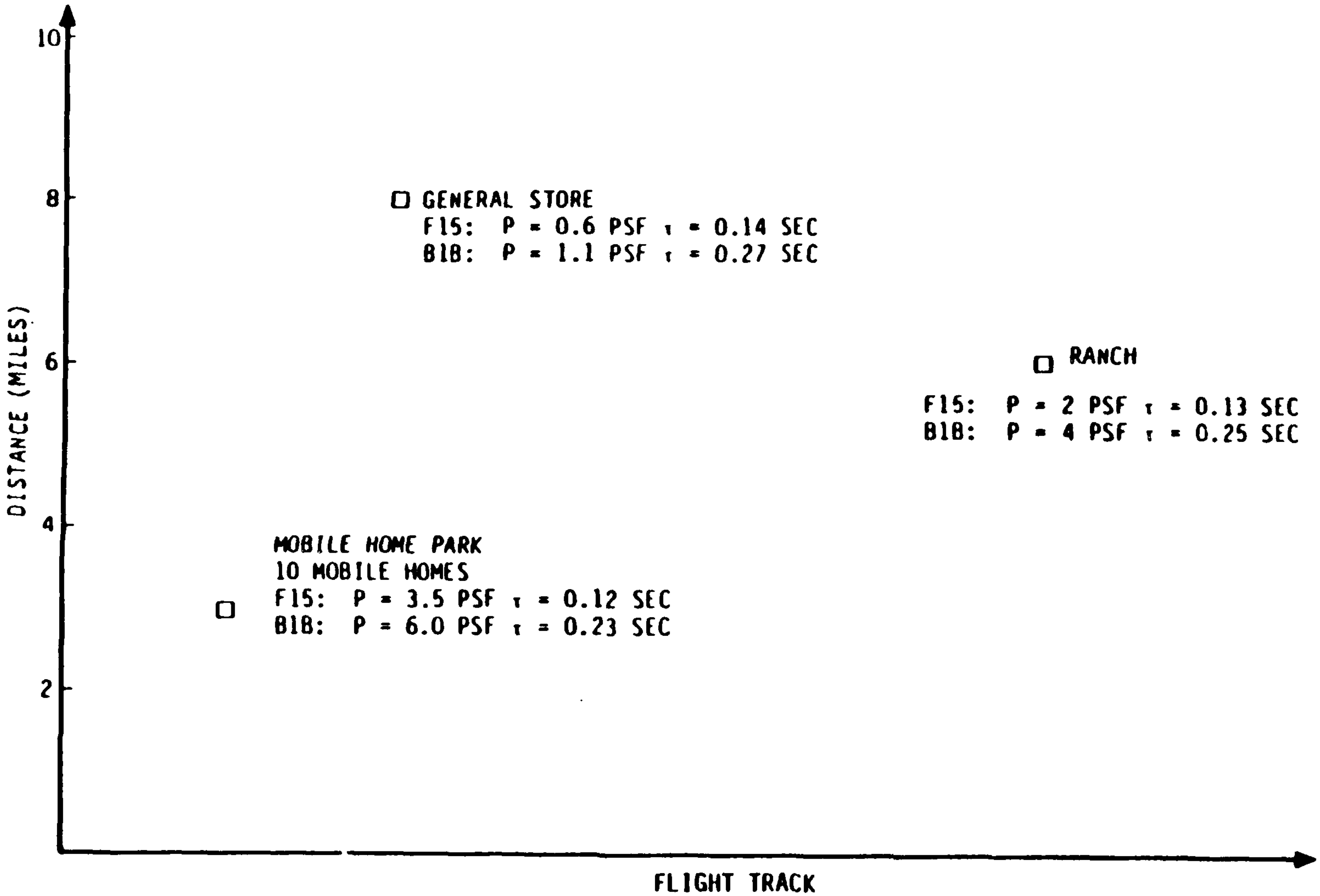

Figure 1-1. Scenario for Comparison of Old and New Damage Assessment Approaches--Low Level Flights of F15 and B1B

construction, while the type B element corresponds to a wood stud plaster wall. Tables 1-5 and 1-6 show the predicted number of plaster elements damaged by the overflights. Both mean and mean plus one standard deviation estimates are shown. Similarly, Tables 1-7 and 1-8 show the predicted number of damaged bric-a-brac items at each site. In the new methodology, the total number of bric-a-brac items at each site is taken to be twice the number of windows.

Table 1-1 Window Inventory for the Example Scenario

	WINDOW CATEGORY			
	A	B	C	TOTAL
MOBILE HOME PARK	50	160	30	240
RANCH	19	14	6	39
GENERAL STORE	--	9	5	14

Table 1-2 Comparison of Predicted Number of Broken Windows For the F-15 Fighter Aircraft Example Scenario Using the Existing Air Force Method and the New Methodology

	EXISTING METHOD	NEW METHOD MEAN	NEW METHOD MEAN + 1σ
MOBILE HOME PARK	3.0×10^{-3}	9.8×10^{-4}	5.7×10^{-2}
RANCH	1.0×10^{-4}	2.4×10^{-8}	1.5×10^{-4}
GENERAL STORE	1.3×10^{-6}	2.0×10^{-8}	1.4×10^{-4}
TOTAL	3.1×10^{-3}	9.8×10^{-4}	5.7×10^{-2}

Table 1-3 Comparison of Predicted Number of Broken Windows For the B1B Bomber Example Scenario Using the Existing Air Force Method and the New Methodology

	EXISTING METHOD	NEW METHOD MEAN	NEW METHOD MEAN + 1σ
MOBILE HOME PARK	1.9×10^{-2}	4.2×10^{-2}	2.7×10^{-1}
RANCH	7.1×10^{-4}	2.4×10^{-4}	2.8×10^{-2}
GENERAL STORE	7.0×10^{-6}	6.9×10^{-7}	3.2×10^{-4}
TOTAL	2.0×10^{-2}	4.2×10^{-2}	3.0×10^{-1}

Table 1-4 Plaster Element Inventory for the Example Scenario

	Plaster Element Category A	Plaster Element Category B
MOBILE HOME PARK	-	40
RANCH	5	6
GENERAL STORE	1	3

Table 1-5 Predicted Number of Damaged Plaster Elements for the F-15 Fighter Aircraft Example Scenario Using the New Methodology

	MEAN	MEAN + 1σ
MOBILE HOME PARK	2.8×10^{-4}	1.2×10^{-2}
RANCH	6.7×10^{-6}	9.5×10^{-4}
GENERAL STORE	1.3×10^{-6}	4.2×10^{-4}
TOTAL	2.9×10^{-4}	1.3×10^{-2}

Table 1-6 Predicted Number of Damaged Plaster Elements for the B1B Bomber Example Scenario Using the New Methodology

	MEAN	MEAN + 1σ
MOBILE HOME PARK	3.6×10^{-2}	2.4×10^{-1}
RANCH	4.8×10^{-3}	3.8×10^{-2}
GENERAL STORE	3.6×10^{-6}	8.7×10^{-4}
TOTAL	4.1×10^{-2}	2.8×10^{-1}

Table 1-7 Predicted Number of Damaged Bric-a-brac Items for the F-15 Fighter Example Scenario Using the New Methodology

	MEAN	MEAN + 1σ
MOBILE HOME PARK	2.2×10^{-5}	4.2×10^{-4}
RANCH	7.0×10^{-9}	1.5×10^{-6}
GENERAL STORE	2.5×10^{-9}	8.7×10^{-7}
TOTAL	2.2×10^{-5}	4.2×10^{-4}

Table 1-8 Predicted Number of Damaged Bric-a-brac Items for the B1B Bomber Example Scenario Using the New Methodology

	MEAN	MEAN + 1σ
MOBILE HOME PARK	1.3×10^{-3}	1.0×10^{-2}
RANCH	3.6×10^{-6}	1.7×10^{-4}
GENERAL STORE	2.5×10^{-9}	8.7×10^{-7}
TOTAL	1.3×10^{-3}	1.0×10^{-2}

The existing Air force method deals only with window glass and makes no provision for predicting damage to plaster and bric-a-brac. While the majority of damage claims from sonic boom activity are attributed to windows, claims for plaster and bric-a-brac are also significant. The new methodology, by including the capacity to predict damage to plaster and bric-a-brac in addition to window glass, offers the environmental planner greater capability in assessing the effects of aircraft operations.

As another means of previewing the capability of the new methodology, the damage predictions using the new method will be compared with the observed damage from overflight tests. A window damage rate of 1.3×10^{-7} broken panes per boom was reported for sonic boom overpressures of 2-3 psf during the Edwards AFB tests (4). The majority of the exposed panes were in housing units. Applying the new methodology and the values tabulated in Appendix A results in pane breakage rates ranging from 3.9×10^{-9} to 6.6×10^{-5} broken panes per boom for an overpressure of 2.5 psf. The variation in breakage estimates is associated with variations in boom duration and the range of overpressures. Thus, the new methodology predicts mean pane breakage rates which bracket the observed breakage at Edwards AFB. (The method currently employed by the Air Force for making these estimates results in an estimate of 2.6×10^{-6} at 2 psf and 8.2×10^{-6} at 3 psf.)

1.3 Organization of Report

The remainder of this report consists of six main sections. Section 2 provides a summary of the current state-of-the-art regarding sonic boom damage to conventional structures. This section also documents mathematical models for sonic damage identified in the course of a literature search. Section 3

presents the model which was selected as a baseline single-event damage model during the course of a literature review. In Section 4 the baseline model is critically reviewed and the sensitivity of the model is evaluated. Section 5 reports the results of an investigation of the current state-of-knowledge regarding cumulative damage effects. Section 6 integrates the results of the earlier material culminating in the specification of a calculation module for ASAN. Section 7 presents the conclusions of this investigation and recommendations for further research. Appendix A contains damage matrices which express the probability of damage to different structural elements to the loading condition. Appendix B contains a set of tables which indicates the contribution of different sources to the uncertainties in Dynamic Amplification Factors. Appendix C provides a nontechnical synopsis of what is known about sonic damage to conventional structures, the "boilerplate" material for ASAN. Appendix D provides a set of damage assessment screens for conventional structures which are contained in the prototype ASAN.

2. LITERATURE SEARCH

The initial phase of this study consisted of a survey of the literature regarding sonic damage to conventional structures from a single overflight. The survey established what is known about the type and extent of damage that may be expected and the existing models for damage prediction. Table 2-1 provides a brief summary of the types of damage which may be expected as a function of overpressure level.

At present, the U.S. Air Force standard model for assessing the effect of sonic boom on structures is the following equation for estimating glass breakage (3):

$$G = 3.85 \times 10^{-7} \times N\ (P)^{2.78} \qquad (2\text{-}1)$$

where G = estimated number of panes of glass broken

N = number of panes of glass exposed to an overpressure level

P = overpressure level to which glass will be exposed

The model assumes that glass breakage is the only damage which may occur, that all windows are equally vulnerable, and that overpressure is the only parameter necessary to characterize the sonic load.

Nineteen additional models were discovered during the literature search. For each of these models the following factors were identified: type of model and its range of applicability, input loading parameters, and structural response or damage outputs yielded. The models were next reviewed to assess whether or not they covered blasting and low-frequency loading forms as well as sonic booms, various materials such as

Table 2-1 Failure Patterns in Conventional Buildings (Adapted from Unpublished Material Developed by Dr. D.R. Webb of RAE)

SONIC BOOM PEAK OVERPRESSURE NOMINAL	ITEMS AFFECTED			SUPPORTING REMARKS
0.5 - 2 psf	Cracks in plaster	Fine; extension of existing; more in ceilings; over door frames; between some plaster boards.	Areas of lath/plaster. Ceilings at ~ 2 psf.	The bulk of these types of 'damages' is in private houses where fragile objects, friable plaster and glass are widespread.
	Cracks in glass	Rarely shattered; either partial or extension of existing.	Glass in rusty frames very vulnerable; can fail at 1 psf (prior faults obvious).	
	Damage to roof	Slippage of existing loose tiles/slates; sometimes new cracking of old slates at nail hole.	Older-type roofs can slip partially or wholly. Confined to roofs when excessive nail corrosion; especially slurry wash roofs.	Modern buildings and industrial complexes are rarely affected.
	Damage to outside walls	Existing cracks in stucco extended.	Old and tall double stone walls can collapse. Always due to prior excessive damage to rubble core.	Stained glass windows not affected unless in very bad condition already.

Table 2-1 Failure Patterns in Conventional Buildings (Continued)

SONIC BOOM PEAK OVERPRESSURE NOMINAL	ITEMS AFFECTED		SUPPORTING REMARKS
0.5 - 2 psf (Continued)	Bric-a-brac	Those carefully balanced or on edges can fall; fine glass, e.g., large goblets.	
	Other	Dust fall in chimneys	Blockage of ducts previously unswept - smoke damage.

SONIC BOOM PEAK OVERPRESSURE NOMINAL	ITEMS AFFECTED		SUPPORTING REMARKS
2 - 4 psf	Glass Plaster Roofs Ceilings	Failures show which would have been difficult to forecast in terms of their existing localized condition. Nominally in good condition.	<u>Glass</u> Worst of these failures, will be caused by a combination of good dynamic coupling and lower-bound (statistical) strength. No glass flying. <u>Plaster</u> Nearly always due to acoustic coupling between the sonic boom and the roof space. Bungalows vulnerable. <u>Roofs</u> Breakage of eroded but otherwise effective nails/pegs. <u>Ceilings</u> Clean breaks in plaster board joints especially in bungalows (coupling effect).

Table 2-1 __Failure Patterns in Conventional Buildings__ (Continued)

SONIC BOOM PEAK OVERPRESSURE NOMINAL		ITEMS AFFECTED	SUPPORTING REMARKS
4 - 10 psf	__Glass__	Regular failures within a population of well-installed glass; industrial as well as domestic; green houses; ships; oil rigs.	Some glass will fail due either to dynamic coupling alone or lower-bound strength alone. Glass pieces can drop out; some flying.
	__Plaster__	Partial ceiling collapse of good plaster; complete collapse of very new, incompletely cured or very old plaster.	Roof space dynamic coupling.
	__Roofs__	High probability rate of failure in nominally good slate, slurry-wash; some chance of failures in tiles on modern roofs; light roofs (bungalow) or large area can move bodily.	Slates/tiles damaged by bounce (acceleration more than 1g) large roofs lifted by negative overpressure part of sonic boom waveform.
	__Walls__ (outside)	Old, free-standing walls in fairly good condition can collapse.	The usual requirement is for the boom wave front to be normal.
	(inside)	'party' walls known to __move__ at 10 psf.	Usually due to acoustic coupling in the room.
Greater than 10 psf	__Glass__	Some good glass will fail regularly to sonic booms from the same direction. Glass with existing faults could shatter and fly. Large window frames move.	Due to forced response: a) edge failures - frame impact; b) center failures - mass stress mode.

Table 2-1 Failure Patterns in Conventional Buildings (Continued)

SONIC BOOM PEAK OVERPRESSURE NOMINAL	ITEMS AFFECTED		SUPPORTING REMARKS
Greater than 10 psf (continued)	Plaster	Most plaster affected.	
	Ceilings	Plaster boards displaced and nail popping.	Large ceiling movements especially in bungalows.
	Roofs	Most slate/slurry roofs affected, some badly; large roofs having good tile can be affected; some roofs bodily displaced causing gable-end and wall-plate cracks; Domestic chimneys - dislodgement if not in good condition.	- Chimneys are not easily affected because they don't couple well with sonic boom characteristics.
	Walls	Internal party walls can move even if carrying fittings such as hand basins or taps; secondary damage due to water leakage.	Mainly due to room acoustic coupling.
	Bric-a brac	Some nominally secure items can fall, e.g., pictures; especially if fixed to party walls.	

plaster, bric-a-brac, roof ('tile'), and, to the extent needed, building structures as well as windows and possible cumulative damage effects. Criteria were defined and were used to select among available models those which may be suitable, when tested against available data bases, for environmental planners to use in assessing the response of conventional structures to acoustic loads from low-altitude subsonic and varying supersonic operations. Finally, using these criteria a baseline model was selected.

These criteria were defined by the following comments. A significant selection criterion was the range of applicability of models. Some models have only limited applicability or address special issues, and cannot easily be used for predictive purposes. If two or more models use generally the same technique, the model least fully developed or with the least experimental or empirical backing was rejected. To assure that the models selected were feasible tools for adaptation for use by an environmental planner, the complexity of the model was also a concern. In the initial phase, the more promising models were subdivided into the following two groups: (1) those models that might be used primarily as tools to investigate some key aspects of structural response or damage from sonic booms and analogous loading waveforms; and (2) those models that serve directly for damage prediction or provide easy-to-use structural response models.

Table 2-2 provides a summary description of the available models identified in this process. Included in this table are author(s), type of analytic model, type of empirical model, type of semi-empirical model and general comments on the model.

Analytic models are further subdivided into single-degree of-freedom (SDOF), two-degree-of-freedom (2DOF) or multi-degree-of-freedom (MDOF) and structural system models,

TABLE 2-2. DESCRIPTION OF AVAILABLE MODELS

No.	AUTHOR(s)	TYPE OF MODEL* SDOF	2DOF/ MDOF	FEM	EMP/ SEMP	ISO	APPLICATION	COMMENTS
+1.	HERSHEY, R.L. HIGGINS, T.H. (1976)				X		WINDOWS, PLASTER, BRICKS, BRIC-A-BRAC	APPLIES GENERALLY TO ANY STRUCTURAL ELEMENT, BASED ON OKLAHOMA CITY & WHITE SANDS MISSILE RANGE TEST DATA.
+2.	WIGGINS, J.H.	X	X		X		WINDOWS, BEAMS	VERY IDEALIZED MODELS, MAXIMUM STRESS FOR BEAM & PLATE, LINEAR REGRESSION MODEL.
+3.	PRETLOVE, A.J. BOWLER, J.F.				X		WINDOWS	LIMITED TO LARGE WINDOWS; ONLY PRELIMINARY ESTIMATE FOR MORE REFINED ANALYSIS. PEAK OVER-PRESSURE LESS THAN 2 PSF.
+4.	CROCKER, M.J. HUDSEN, R.R.	X					WINDOWS, BEAMS, ETC.	APPLICABLE TO ANY STRUCTURAL ELEMENT. DAMPING IS INCLUDED. VERY IDEALIZED.
+5.	PROULX, J.	X			X		WALL STUD	MEAN AND VARIANCE OF RESPONSE DUE TO PREDICTED WAVE IS COMPARED WITH THAT OF MEASURED WAVE.

*SDOF = SINGLE-DEGREE-OF-FREEDOM MODEL, 2DOF = 2-DEGREE-OF-FREEDOM MODEL, EMP = EMPIRICAL MODEL, MDOF = MULTI-DEGREE-OF-FREEDOM MODEL, SEMP = SEMI-EMPIRICAL MODEL, FEM = FINITE ELEMENT MODEL,
+PROVISIONALLY ACCEPTED MODELS, ISO = ISOAMPLITUDE CONTOUR METHOD.

TABLE 2-2. (CONTINUED)

No.	AUTHOR(s)	TYPE OF MODEL* SDOF	2DOF/ MDOF	FEM	EMP/ SEMP	ISO	APPLICATION	COMMENTS
+6.	ROLAND, S.		X				STAINED WINDOW	IDEALIZED MODEL, CONSIDERS AGING & DETERIORATION. SUPPORT MOVEMENTS ARE STUDIED.
+7.	POPPLEWELL, N.			X			BEAMS, PLATES, BOX	INEXPENSIVE ONLY FOR SIMPLE SINGLE STORY BUILDING. DETAILED STUDY IS POSSIBLE.
8.	LIN, S.	X					PARTIALLY OPENED WINDOWS	AIR CAVITY COUPLING EXAMINED. INTERNAL ACOUSTIC RESPONSE IS MODELED BY ELECTRICAL ANALOGUE.
9.	KOOPMAN, L. POLLARD, H.	X					WINDOWS	AIR CAVITY COUPLING IS MODELED FOR WINDOW & DOOR BY HELMHOLTZ RESONATOR. NO RESONANCE WAS DETECTED.
10.	SESHADRI, T.V. LOWERY, R.L.	X	X				WINDOWS	MECHANO-ACOUSTICAL MODELING: AIR CAVITY COUPLING OF ROOM, WINDOW & HALLWAY: TOO COMPLEX.

*SDOF = SINGLE-DEGREE-OF-FREEDOM MODEL, 2DOF = 2-DEGREE-OF-FREEDOM MODEL, EMP = EMPIRICAL MODEL, MDOF = MULTI-DEGREE-OF-FREEDOM MODEL, SEMP = SEMI-EMPIRICAL MODEL, FEM = FINITE ELEMENT MODEL,
+PROVISIONALLY ACCEPTED MODELS, ISO = ISOAMPLITUDE CONTOUR METHOD.

TABLE 2-2. (CONTINUED)

No.	AUTHOR(s)	TYPE OF MODEL* SDOF	2DOF/ MDOF	FEM	EMP/ SEMP	ISO	APPLICATION	COMMENTS
11.	SEAMAN, L.	X					WINDOWS	LINEAR ELASTIC; SIMPLE SUPPORTS. ATTEMPTED TO PREDICT STATISTICALLY BUT FAILED OWING TO LACK OF GLASS STRENGTH DATA.
12.	CHENG, D.H. BENVENISTE, J.E. (1969)	X					PLATE, BEAM	UNIFORM PLATE MODEL APPLICABLE TO VARIOUS STRUCTURAL ELEMENTS. ASSUMES SIMPLE SUPPORTS AND LINEAR ELASTIC PROPERTIES.
13.	CHENG, D.H. BENVENISTE, J.E. (1966)	X					BEAM	ASSUMES LOOSE SUPPORTS, UNIFORM CROSS-SECTION. LIMITED TO BEAMS. TOO COMPLEX FOR PLATES.
14.	HERSHEY, R.L. HIGGINS, T.H. MAGRAB, E.B.				X		WINDOWS	PROBABILITY OF GLASS FAILURE BASED ON PROBABILITY OF GLASS STRENGTH AND OVERPRESSURE. LINEAR ELASTIC PROPERTIES.
15.	HERSHEY, R.L. HIGGINS, T.H. (1975)				X		WINDOWS	STATISTICAL MODEL TO DESIGN WINDOWS: BASED ON TEST DATA FROM OKLAHOMA, WHITE SANDS AND EDWARDS AIR FORCE BASE.

*SDOF = SINGLE DEGREE OF FREEDOM MODEL, EMP = EMPIRICAL MODEL, 2DOF = 2-DEGREE-OF-FREEDOM MODEL, MDOF = MULTI DEGREE OF FREEDOM MODEL, SEMP = SEMI-EMPIRICAL MODEL, FEM = FINITE ELEMENT MODEL, ISO = ISOAMPLITUDE CONTOUR METHOD.

TABLE 2-2. (CONTINUED)

No.	AUTHOR(s)	TYPE OF MODEL* SDOF	2DOF/ MDOF	FEM	EMP/ SEMP	ISO	APPLICATION	COMMENTS
16.	CRAGGS, A.	X					PLATES	NUMERICAL INTEGRATION. HIGHLY THEORETICAL. NO PRACTICAL SIGNIFICANCE. LINEAR ELASTIC PROPERTIES.
17.	COLEBY, J.R. MAZUMDAR, J.					X	WINDOWS	PLATE CAN BE ANY SHAPE, VERY COMPLEX FOR PRACTICAL USE. LINEAR ELASTIC: SIMPLE & CLAMPED SUPPORT CONDITIONS.
18.	ALWAR, R.S. NATH, Y.	X					PLATES	APPLIES ONLY TO CIRCULAR SHAPE. NON-LINEAR BEHAVIOR FROM LARGE DEFLECTION IS USED; APPLIES TO ANY LINEAR ELASTIC MATERIALS.
19.	SLUTSKY, S. ARNOLD, L.			X			WINDOWS, PLATES, ETC.	DISCRETE ELEMENTS: USED FOR EXAMINATION OF ARCHAEOLOGICAL DAMAGE. LINEAR ELASTIC.

*SDOF = SINGLE DEGREE OF FREEDOM MODEL, EMP = EMPIRICAL MODEL, 2DOF = 2-DEGREE-OF-FREEDOM MODEL, MDOF = MULTI DEGREE OF FREEDOM MODEL, SEMP = SEMI-EMPIRICAL MODEL, FEM = FINITE ELEMENT MODEL, ISO = ISOAMPLITUDE CONTOUR METHOD.

especially structural finite element models (FEM) and isoamplitude contour method (ISO). The applications of each model identified are also indicated. Table 2-3 further elaborates these models in terms of input parameters required and outputs that can be produced.

The models selected in this table represent those models from the literature search that showed initial plausibility, or backing for use as partial model elements, or complete, comprehensive models in estimating potential damage from low-flying subsonic or supersonic flights. The models identified at this stage potentially cover the entire range of structural effects topics for conventional structures of concern to the environmental planner. Most of the models cover structural window response or damage prediction. Several of the models could be used to cover plaster response. Some of the models could be used to cover bric-a-brac response. To the extent needed, some of the models could be used to cover overall structural response, including response of ceilings and walls.

Although no single existing model is totally satisfactory, model number one developed by R. Hershey and T. Higgins (2) most closely meets the objective of providing a tool for use by an environmental planner in assessing the damage expected from a proposed set of supersonic operations. This model was adopted as the baseline model. The second through seventh models were identified as potentially useful tools for investigating and refining the baseline model.

The baseline model is an enhancement of earlier work by these investigators (1). The vulnerability of windows to sonic booms was the subject of their original study. The baseline model addresses not only window damage, but also potential damage to plaster walls and ceilings, bric-a-brac, and brick

walls. Furthermore, one of the investigators (9) has applied an extension of the baseline model to unconventional structures subjected to noise from subsonic aircraft.

TABLE 2-3. CHARACTERISTICS OF IDENTIFIED MODELS

No.	AUTHOR(s)	INPUT PARAMETERS: LOADING FUNCTION P_o^+	T_N	T_r	P_o^-	OTHER	STRUCTURAL PROPERTIES	OUTPUT PARAMETERS: STRESS	DEFL.	COMMENTS
+1.	HERSHEY, R.L. HIGGINS, T.H. (1976)	V	V	V	--	SB	GLASS, CEILINGS, PLASTER.	X	X	PROBABILITY MODEL, (DAF) IS CALCULATED
+2.	WIGGINS, J.H.	V	V	V	--	SB	ELASTIC WINDOWS, WALL, ETC.	--	X	DEFLECTIONS
+3.	PRETLOVE, A.J. BOWLER, J.F.	*	**	--	--	SB	UNIFORM RECTANGLE, LARGE PLATE	X	X	CENTRAL DEFLECTION & STRESS
+4.	CROCKER, M.J. HUDSEN, R.R.	V	V	V	V	SB	MASS AND DAMPING PROPERTIES.	--	X	DYNAMIC AMPLIFICATION FACTOR
+5.	PROULX, J.	V	V	V	--	SB	LINEAR ELASTIC.	--	X	DYNAMIC AMPLIFICATION FACTOR

V = VARIABLE INPUT, SB = SONIC BOOM WAVE, A = ANY WAVE FORM, X = VARIABLE CONSIDERED,
* = BASED ON OVERPRESSURE LESS THAN 2 PSF, ** = DURATION IS 200 AND 400 MS., T_r = RISE TIME,
P_o^+ = PEAK POSITIVE OVERPRESSURE, P_o^- = PEAK NEGATIVE OVERPRESSURE, T_N = WAVE DURATION,
+PROVISIONALLY ACCEPTED MODELS.

TABLE 2-3. (CONTINUED)

No.	AUTHOR(s)	INPUT PARAMETERS: LOADING FUNCTION P_o^+	T_N	T_r	P_o^-	OTHER	STRUCTURAL PROPERTIES	OUTPUT PARAMETERS: STRESS	DEFL.	COMMENTS
+6.	ROLAND, J.	V	V	V	--	SB	PLATE; LINEAR ELASTIC.	--	X	DISPLACEMENT, SUPPORT VIBRATION IS NOTED
+7.	POPPLEWELL, N.	V	V	V	V	SB	MASS & DAMPING.	X	X	DISPLACEMENTS, STRESSES.
8.	LIN, S.	V	V	V	--	SB	MASS AND DAMPING; LINEAR ELASTIC.		X	RESPONSE OF COUPLED ROOMS: DISPLACEMENT-TIME HISTORY.
9.	KOOPMAN, G. POLLARD, H.	V	V	V	--	A	SIMPLY SUPPORTED; LINEAR ELASTIC.	--	X	CENTRAL DEFLICTIONS
10.	SESHADRI, T.V. LOWERY, R.L.	V	V	V	V	SB	SIMPLE SUPPORTS: LINEAR ELASTIC.	X	--	MAXIMUM STRESS FOR UNDAMPED AND DAMPED CONDITIONS.

V = VARIABLE INPUT, SB = SONIC BOOM WAVE FORM, A = ANY WAVE FORM, T_N = WAVE DURATION,
X = VARIABLE CONSIDERED, P_o^+ = PEAK POSITIVE OVERPRESSURE, P_o^- = PEAK NEGATIVE OVERPRESSURE,
T_r = RISE TIME, +PROVISIONALLY ACCEPTED MODELS.

TABLE 2-3. (CONTINUED)

		INPUT PARAMETERS						OUTPUT PARAMETERS		
No.	AUTHOR(s)	LOADING FUNCTION					STRUCTURAL PROPERTIES	STRESS	DEFL.	COMMENTS
		P_o^+	T_N	T_r	P_o^-	OTHER				
11.	SEAMAN, L.	V	V	V	--	SB	MASS AND DAMPING, RECTANGLE.	X	--	LINEAR AND NON LINEAR DEFLECTIONS
12.	CHENG, D.H. BENVENISTE, J.E. (1969)	V	V	V	V	A	MASS AND DAMPING; SIMPLE SUPPORT.	--	X	MAX. MOMENTS; (DAF) AT MIDSPAN
13.	CHENG, D.H. BENVENISTE, J.E. (1966)	V	V	V	V	SB	BEAM; MASS & DAMPING; LOOSE SUPPORT.	--	X	(DAF) FOR DEFLECTION
14.	HERSHEY, R.L. HIGGINS, T.H. MAGRAB, E.B.	V	V	V	--	SB	MASS AND DAMPING; LINEAR ELASTIC.	--	--	PROBABILITY OF GLASS BREAKAGE
15.	HERSHEY, R.L. HIGGINS, T.H. (1975)	V	V	V	V	SB	LINEAR ELASTIC; SIMPLE SUPPORT.	--	--	PROBABILITY MODEL TO WINDOW DESIGN

V = VARIABLE INPUT, SB = SONIC BOOM WAVE FORM, A = ANY WAVE FORM, T_N = WAVE DURATION, P_o^+ = PEAK POSITIVE OVERPRESSURE, P_o^- = PEAK NEGATIVE OVERPRESSURE, T_r = RISE TIME, X = VARIABLE CONSIDERED.

TABLE 2-3. (CONTINUED)

		INPUT PARAMETERS						OUTPUT PARAMETERS		
No.	AUTHOR(s)	LOADING FUNCTION					STRUCTURAL	STRESS	DEFL.	COMMENTS
		P_o^+	T_N	T_r	P_o^-	OTHER	PROPERTIES			
16.	CRAGGS, A.	V	V	V	V	A	SIMPLE SUPPORTS: LINEAR ELASTIC.	X	X	DISPLACEMENT, ACCELERATION OF RESPONSE
17.	COLEBY, J.R. MAZUMDAR, J.	V	V	V	--	SB/ BLAST	RECTANGLE, TRIANGLE, PLATES.	--	X	CENTRAL LONGI- TUDINAL DEFL. & STRAINS
18.	ALWAR, R.S. NATH, Y.	V	V	V	V	SB	LINEAR ELASTIC; SIMPLE SUPPORTS.	--	X	DYNAMIC AMPLIFICATION FACTOR
19.	SLUTSKY, S. ARNOLD, L.	V	V	V	--	SB	LINEAR ELASTIC.	--	X	DISPLACEMENT- TIME HISTORY

V = VARIABLE INPUT, SB = SONIC BOOM WAVE FORM, A = ANY WAVE FORM, T_N = WAVE DURATION,
P_o^+ = PEAK POSITIVE OVERPRESSURE, P_o^- = PEAK NEGATIVE OVERPRESSURE, T_r = RISE TIME,
X = VARIABLE CONSIDERED.

3. THE BASELINE MODEL

3.1 Introduction

The Hershey and Higgins model was adopted as the baseline model for sonic boom damage prediction. They first proposed this model for prediction of glass breakage from sonic boom loads and later adapted it to include plaster, bric-a-brac and brick damage from these loads and to damage to elements of historical structures from Concorde subsonic noise. The form of the model is sufficiently general to be adaptable to a wide variety of loads and structures.

The model is based upon a few simple assumptions. The variations of loads that may occur are treated as due to random factors and the result is a stress (which is a random variable) applied to a structural element. The breaking strength of the structural element is, similarly, regarded to be a random variable. An effective factor of safety is defined by

$$\text{Factor of Safety} = (\text{Breaking Strength})/(\text{Applied Stress}) \qquad (3\text{-}1)$$

The assumption is made that breaking strength and applied stress are statistically independent. The probability distribution for the factor of safety may then be computed by evaluating a convolution integral of the breaking strength and the applied stress. Knowing the probability distribution for the factor of safety provides the probability of failure for any combination of load and capacity.

This relationship is then simplified by taking logarithms of both sides giving

$$\text{Log(FS)} = \text{Log(Strength)} - \text{Log(Stress)} \qquad (3\text{-}2)$$

Since both terms on the right side of the equation are assumed to have probability distributions which are normal, Log(Factor of Safety) is normally distributed so that the Factor of Safety is lognormally distributed. This distribution results in an equation for the probability of breakage which is easy to evaluate.

The approach adopted by Hershey and Higgins is heavily weighted toward the use of field data to develop the parameters of the probability distributions of load and capacity; it incorporates explicitly more detailed dependencies than many other such models. To characterize the loads they relied upon three sets of data:

1. Oklahoma City Sonic Boom Tests performed by the Federal Aviation Administration (FAA) and the National Aeronautical and Space Administration (NASA) in 1964.
2. White Sands, N. Mex., Sonic Boom Structural Reaction Tests performed by FAA in 1965.
3. Edwards Air Force Base Sonic Boom Tests performed by FAA and NASA in 1966.

The glass breakage analysis, their initial work, relied upon Libbey-Owens-Ford laboratory strength tests. Since their treatment of other materials is an extension of this basic work, the modifications to accommodate other materials will be presented after those for the window model.

Hershey and Higgins model windows as simply supported plates. Thus, failure occurs due to the maximum stress, σ_m, in the middle of the plate. They adopt the following constitutive relationship for the maximum stress

$$\sigma_m = P_o\ (P_f/P_o)\ (P_e/P_f)\ (\sigma_d/P_e)\ (\sigma_m/\sigma_d) \qquad (3\text{-}3)$$

where P_o = nominal (peak) overpressure <u>including modeled reflection factor</u>

P_f = actual ground level (peak) overpressure including reflection factor

P_e = peak external pressure applied to a particular structural element, including orientation effects and metastructural effects such as adjacent structural elements and internal resonance

σ_d = static stress = $(P_e\ a^2b^2)/(2h^2\ (a^2 + b^2))$

a,b,h = plate length, width and thickness

σ_m/σ_d = dynamic amplification factor, DAF

F = (σ_d/P_e) = geometry/materials factor

Using this notation they express the breaking strength of a glass pane, σ_G, in terms of a breaking pressure, P_G, as

$$\sigma_G = F\ P_G \tag{3-4}$$

In Equations 3-3 and 3-4 they treat the following variables as random variables: (P_f/P_o), (P_e/P_f), DAF, and P_G. The remaining variables are treated deterministically.

3.2 Development of Probability Distributions

The Oklahoma City tests involved overflights by four types of aircraft: F-104, F-101, F-106, and B-58. Hershey and Higgins employed F-101 and F-104 data for analysis. Nominal overpressures for these flights ranged from 0.64 psf to 2.17 psf. Three sets of measurements were obtained: one approximately underneath the flight track; one from a station 5 miles from the flight track; and one from a station 10 miles from the flight track. A typical set of flight conditions was an altitude of 28,000 ft at Mach 1.5. Hershey and Higgins fit the data for the third station for the ratio of freefield pressures to nominal pressures with a lognormal distribution and applied this distribution to the entire sonic boom carpet.

The White Sands tests involved F-104s and B-58s, generally flying at lower than normal altitudes to create high overpressures. Freefield test overpressures were often in the 10-20 psf range but included values as low as 1 psf. The Hershey/Higgins study employed the freefield overpressure measurements together with measurements of external pressures at the center of the walls of a structure designated as W4. For each overflight the direction of the flight vector to the nearest 45 degrees, the freefield overpressure and the external overpressures were recorded. A regression analysis using these discrete headings, θ, gave the relationship

$$\mathrm{Log}(P_e/P_f) = 0.1427 \cos\theta - 0.1258 \tag{3-5}$$

They also analyzed these data to obtain means and variances for $\mathrm{Log}(P_e/P_f)$ for head-on flights and for all flights.

In addition, two of the windows on test structure W4 were instrumented with strain gauges. Gauges were located at the center of the windows. The maximum stress was derived from the measured strains. Using the measured value of P_e and the geometry factor, F, DAFs could be directly calculated.

An additional set of DAF statistics were developed for five windows at Edwards Air Force Base using measured strains, measured freefield pressures and the regression relationship (Equation 3-5) between aircraft heading and $\mathrm{Log}(P_e/P_f)$.

The Edwards AFB tests involved overflights of B-58, XB-70, F-104 and SR-71 aircraft. These ranged from about 18,000 ft at typical speeds of Mach 1.3 to over 60,000 ft at speeds up to Mach 2.5. Significantly, the mix of testing at both White Sands and Edwards included a wide variation in duration of the loading waveforms.

Glass breaking strengths were derived from a set of laboratory tests performed on new glass by Libbey-Owens-Ford. Each glass pane was glazed in the opening of a special test chamber. Uniform loads were applied by creating a vacuum in the test chamber. Each load level was maintained for 1 minute. Loads were increased until the glass broke. Hershey and Higgins developed the following empirical formula for mean breaking pressures

$$P_G = (25946\ h^{1.54})/A \qquad (3\text{-}6)$$

where P_G = breaking load in psf
h = plate thickness in inches
A = plate area in feet^2

Their data suggest that this breaking load is lognormally distributed. Hershey and Higgins modeled the increase in strength due to the decreased duration of the load by doubling the mean of the distribution. To adjust for the fact that glass in the field is not new, they used limited data to justify reducing the mean by a factor of two. This double adjustment resulted in their using the test data for glass breaking strength.

To account for precracked glass or glass that has been improperly mounted the category of precracked glass was introduced. Based on a survey of experts in the glass community they assume that precracked glass has one-tenth the mean strength of used glass and the same variance of the logarithm of strength as used glass. Based on a survey of the community surrounding Edwards AFB they conclude that 0.61% of the population of glass is precracked. The total probability of breakage they model as

$$P = 0.9939P_H + 0.0061P_C \qquad (3\text{-}7)$$

where the first term is the contribution due to healthy used glass and the second term is the contribution due to pre-cracked glass.

The window characteristics and key model assumptions used by Hershey and Higgins to model these windows are presented in Table 3-1.

Table 3-1 Hershey/Higgins Model Parameters for Window Damage

AREA (SQ FT)	Fo (HZ)	TYPE	LOG (PG) MEAN	LOG (PG) VARIANCE	LOG(DAF) MEAN	LOG(DAF) VARIANCE
17.0	13.0	USED	1.794	0.0102	-0.012	0.0118
3.8	56.0	USED	2.105	0.0100	0.258	0.0152
58.4	5.7	USED	1.688	0.0051	-0.123	0.0206
107.0	4.0	USED	1.461	0.0085	-0.149	0.0458
0.84	188.1	USED	2.402	0.0058	0.398	0.0719
47.0	7.9	USED	1.765	0.0135	0.080	0.0508
14.4	21.9	USED	2.145	0.0141	-0.088	0.0803
17.0	13.0	CRCKD	0.794	0.0102	-0.012	0.0118
3.8	56.0	CRCKD	1.105	0.0100	0.258	0.0152
58.4	5.7	CRCKD	0.688	0.0051	-0.123	0.0206
107.0	4.0	CRCKD	0.461	0.0085	-0.149	0.0458
0.84	188.1	CRCKD	1.402	0.0058	0.398	0.0719
47.0	7.9	CRCKD	0.765	0.0135	0.080	0.0508
14.4	21.9	CRCKD	1.145	0.0141	-0.088	0.0803

	MEAN	VARIANCE
$LOG(P_f/P_o)$	0.047	0.0446
$LOG(P_e/P_f)$	-0.125	0.0439

Hershey and Higgins justify their model by the <u>assertion</u> that the results it predicts for a <u>healthy overall glass population</u> (1.1×10^{-6} at 1 psf) match claims data well.

3.3 Confidence Bounds for Probability Estimates

Finally, Hershey and Higgins outline a procedure for calculating a confidence bound on their damage estimates. They assume in deriving this confidence bound that the only source of uncertainty in developing their statistics was the use of finite sample sizes to estimate the probability distributions; that is, no uncertainty was introduced by the form of their model, by aggregation or by any other source. Their procedure is as follows: Calculate the variance of the estimate of the mean of the logarithm of the factor of safety by the weighted sum of the variances of the four random variables (see Equations 3-3 and 3-4) composing it. The weights are the number of samples used to generate the original estimates. The next step is the formation of a confidence interval. This interval is expressed in terms of the following three factors: (1) the estimate of the mean of the logarithm of the factor of safety, (2) the value of the standard normal random variable corresponding to the desired confidence level, and (3) the estimate of the variance of the mean. They report at the 99% level that this procedure results in confidence intervals a factor of three wide.

3.4 General Observations

In comparison to other models for window breakage from sonic booms or air blast, Hershey and Higgins have proposed a relatively complex model for developing the load. On the capacity side, the model is intermediate in complexity in the sense that it distinguishes glass panes by size and prior condition (precracked or not). This emphasis on the load is also seen in the proposed distribution for the logarithm of the factor of safety. Less than 10% of the variance in the logarithm of the factor of safety is based on the variance in the capacity of the glass; the remainder comes from variances of

terms used to define the load. Typically, the variance in DAF or P_f/P_o is the dominant term.

3.5 Extensions to Other Building Elements

In their more recent work Hershey and Higgins have extended the model previously described to plaster, bric-a-brac, and bricks. The following discussion characterizes these model extensions.

3.5.1 Plaster

Unlike glass, plaster never occurs alone as a building material, but rather is used in conjunction with some supporting material. Further, almost all sonic boom plaster damage consists of hairline cracks or extensions of existing cracks. Two types of failure occur: In **diaphragm** failure the wall or ceiling bellies out due to the load, and bends the plaster on its surface; in **racking** failure adjacent building elements lean forward tending to distort the wall into a parallelogram. Racking failures tear plaster near the corner of the room and near doors and windows. Arguing that both types of failures occur at about the same overpressures, that racking failures are much more difficult to treat analytically, and that data on these failures are scarce, the authors elect to consider diaphragm failures only. This choice allows them to employ an extension of the plate model that they used for glass.

Characterization of the load for plaster elements follows the same format as for glass with the following exceptions. Two categories of plaster building elements are addressed--ceilings and walls. For ceilings, it is assumed that the sonic boom passing through the roof and attic has been attenuated so that

different statistics apply for P_e/P_f than for the exterior loads for glass. These are:

$$\text{Mean } \{\text{Log}(P_e/P_f)\} = -0.1609 \qquad (3\text{-}8)$$
$$\text{Variance } \{\text{Log}(P_e/P_f)\} = 0.0029$$

Wall elements are treated as though they receive the same external pressure as windows. For all plaster elements Hershey and Higgins use the DAF statistics previously assembled for the largest window for which they had data, a 107 ft^2 (32.6 m^2) simply supported window:

$$\text{Mean } \{\text{Log}(\text{DAF})\} = -0.1489 \qquad (3\text{-}9)$$
$$\text{Variance } \{\text{Log}(\text{DAF})\} = 0.0458$$

Hershey and Higgins made no adjustment for the differences in materials between glass and plaster walls nor for variation with duration of loading waveform.

Six plaster configurations were considered: two ceilings--one with a low strength plaster (tensile strength of 100 psi) and one with a high strength plaster (tensile strength of 350 psi), two party walls, and two exterior walls. The differences between the pairs of party walls and exterior walls were the other materials supporting the plaster. Distribution means were taken from laboratory tests. No probability distribution data were available for plaster. Since many of the factors (workmanship, amount of water used, composition of mixture, etc.) contributing to the variation in plaster strength also affect the strength of mortar, and since probability distribution data were available for mortar, the authors adopted the variance of the logarithm of the breaking strength of mortar to be used as the variance of the logarithm of the breaking strength of plaster.

Variance {Log(Breaking Pressure)} = 0.0324 (3-10)

The parameters used to model plaster damage are shown in Table 3-2.

Table 3-2 Hershey/Higgins Model Parameters for Plaster Damage

ELEMENT TYPE	LOG (PG) MEAN	LOG (PG) VARIANCE	LOG (P_e/P_f) MEAN	LOG (P_e/P_f) VARIANCE
CEILINGS				
100 psi tensile strength	1.041	0.0423	-0.1609	0.0029
350 psi tensile strength	1.591	0.0324	-0.1609	0.0029
PARTY WALLS				
Light Weight	1.176	0.0324	-0.125	0.0439
Heavy Weight	1.415	0.0324	-0.125	0.0439
EXTERIOR WALLS				
Light Weight	1.699	0.0324	-0.125	0.0439
Heavy Weight	1.778	0.0324	-0.125	0.0439

	MEAN	VARIANCE
LOG (DAF)	-0.149	0.0458

3.5.2 Bric-a-brac

The term bric-a-brac is used to refer to miscellaneous ornamental objects, such as ashtrays or figurines, which sit on surfaces such as tables or shelves. Excluded are hanging objects such as pictures and mirrors. Vulnerability of these objects depends on their delicacy, their stability, and their location (proximity to an edge of their supporting surface).

There are no natural categories for bric-a-brac. In addition, because inventories of bric-a-brac are not readily available, Hershey and Higgins fitted two data points to their lognormal breakage model.

The first data point was derived from Edwards AFB claims data. The nominal overpressure at which this damage occurred was 2 psf. The ratio of bric-a-brac claims to glass claims for this incident was 3 to 58. The authors inventoried their homes and came to the conclusion that the average home has twice as many items of bric-a-brac as windows. The authors then scaled their estimate of the breakage probability at 2 psf of the overall population of **healthy** glass to get an estimate of the bric-a-brac breakage probability per item:

$$(3.4\times10^{-5}) \times (3/58) \times (1/2) = 8.8\times10^{-7} \qquad (3\text{-}11)$$

The second data point resulted from the White Sands test at 38 psf. Two out of an estimated 900 pieces of bric-a-brac in the test houses were broken at this pressure.

3.5.3 Brick

The authors begin by appealing to nuclear effects literature to argue that the probability of knocking down a brick wall of a dwelling would be no greater than 1×10^{-15} even for a 100 psf sonic boom. They then go on to develop probability distributions for assessing potential damage to free-standing brick walls. Four types of brick walls (all 4 ft (1.2 m) wide by 8 ft (2.4 m) high) were tested by the National Bureau of Standards (NBS) using an air bag technique to create the pressure load. These test results were used to provide the means of the strength distribution; the previously mentioned variance of the logarithm of the strength of mortar was assumed to apply to the brick strength. This capacity model was used

with the load model described for glass. Key characteristics of the brick walls modeled are shown in Table 3-3.

Table 3-3 STATIC FAILURE PRESSURES OF BRICK WALLS
(Hershey & Higgins)

No.	BRICK DESCRIPTION	BRICK DIMENSIONS (INCHES)	MORTAR TYPE	RUPTURE MODULUS (PSI)	STATIC PG (PSF)	LOG(PG) MEAN	LOG(PG) VARIANCE
1	Cream colored, extruded wire-cut units with 3 round cores	3.63x7.97x2.25	1:1:4	850	17.3	1.238	0.0324
2	Red, extruded, wire-cut units with no cores	3.62x8.00x2.26	HIGH-BOND	740	57.6	1.760	0.0324
3	Cream colored, extruded wire-cut units with 3 round cores	3.63x7.97x2.25	HIGH-BOND	850	83.5	1.922	0.0324
4	Gray, extruded, wire-cut units with 5 oval cores	3.75x8.08x2.25	HIGH-BOND	760	158.4	2.200	0.0324

4. EVALUATION OF THE BASELINE MODEL

4.1 Introduction

This section presents the results of a comprehensive review of the model developed by Hershey and Higgins. Key findings of this review are as follows:

1. The constitutive relationships adopted by Hershey and Higgins for their model are sound. The form of the model is sufficiently flexible to allow it to be adapted to other loads (e.g., subsonic noise), to other types of structures (unconventional structures), and to damage from repetitive sonic boom loads (cumulative damage).

2. At common sonic boom overpressures, damage results from "exceptional" conditions. These conditions include materials which had been damaged or weakened prior to exposure to sonic booms, elements with stress raisers, and metastructural effects which enhance the effective loads over those anticipated. Metastructural effects include load modification by diffraction, reflection and internal (Helmholtz) resonance of a structure.

The baseline model addresses reduced glass capacity due to preweakening. <u>The validity of the statistics proposed for this preweakened glass are unknown, although they appear "reasonable"</u>. No treatment is included for preweakened plaster.

The uncertainty in effective load due to metastructural effects is included in the baseline model. The form in which it is included is inappropriate, as noted later.

3. The probability distributions employed in the model are a practical choice for a model that must be used repeatedly by planners. In those instances for which data are available, the probability distributions are consistent with the empirical data. In some instances, equally valid arguments for other probability distributions exist in the literature. **Inadequate data exist to evaluate the tails of these distributions which are the most critical portion for sonic boom loads**.

4. The relationship for the maximum stress consists of the product of two factors which are treated as deterministic and three factors which are treated as random variables. It was necessary to correct the statistics for two of the random variables and change the treatment of the variability in the third from contributing to damage assessment to contributing to the uncertainty in the damage assessment.

5. The capacity model is the product of a deterministic factor and a random variable. It was necessary to revise the statistics for the random variable.

6. Adaptation of the model as a practical tool requires a certain amount of categorization (for example, loads may be characterized as an overpressure interval and a duration interval; all windows having a surface area within a given range may be treated as having common properties). This categorization, together with the shift in the treatment of one of the baseline model's "random variables" to a categorization type variable, all contribute to the uncertainty in the damage estimates. A damage uncertainty model is proposed which addresses all these factors (see Section 6).

This review will examine each factor of the model and, where appropriate, discuss an alternative treatment. (Section 6 presents a detailed discussion of the recommended form of the model for NSBIT usage.) The order of development will track the order used in the presentation of the baseline model: windows will be discussed first followed by other elements. Within the basic discussion on windows the modeling of loads will be addressed before that of capacity.

4.2 Window Damage Model

Recall that the constitutive relationship proposed for maximum stress is

$$\sigma_m = P_o \, (P_f/P_o) \, (P_e/P_f) \, (\sigma_d/P_e) \, (\sigma_m/\sigma_d) \tag{4-1}$$

or

$$\sigma_m = P_o \, (P_f/P_o) \, (P_e/P_f) \, (F) \, (DAF)$$

and that the constitutive relationship proposed for breaking strength is

$$\sigma_G = F \, P_G \tag{4-2}$$

The first factor in Equation 4-1, P_o, is treated deterministically. For those applications for which every exposure of each element at risk can be separately calculated, this is appropriate.

The second factor, the ratio of the freefield overpressure to the nominal overpressure, is a random variable. The probability distribution employed in the existing model is appropriate near the edge of the sonic boom carpet. Up to a distance of approximately 80% of the distance to cutoff the probability distribution is much narrower.

In the central portion of the sonic boom carpet the probability distribution has the following characteristics. The empirical distribution of the ratio is well approximated by a lognormal distribution. The mean of $\log(P_f/P_o)$ is -0.075; this corresponds to a value for P_f/P_o of 0.84 -- a slight overprediction of pressures. The magnitude of the coefficient of variation of $\log(P_f/P_o)$ is 0.84 (5). The empirical distribution of the ratio near the edge of the sonic boom carpet is also well approximated by the lognormal distribution. However, in this region the mean of $\log(P_f/P_o)$ is 0.047 which corresponds to a value for P_f/P_o of 1.11 -- a slight underprediction of pressures. The coefficient of variation of $\log(P_f/P_o)$ is 4.5 -- a factor of more than 5 larger than that for the central portion of the sonic boom carpet.

Normally, the overpressures are so low at the distances from the flight track at which the Hershey and Higgins distribution is valid that they make an insignificant contribution to the expected damages. Since this situation is the case for sonic booms expected to be of concern to NSBIT, the distribution determined in Reference 5 should be adopted universally for nonfocused sonic booms. Should a situation arise in which the maneuvers being analyzed produce significant overpressures at the sonic boom carpet margins (for example, extremely low level supersonic flight), then the Hershey and Higgins distribution for (P_f/P_o) should be used in the sonic boom carpet margins.

The location at which a focused sonic boom will occur and the form of the signature are highly sensitive to the specific maneuver the aircraft was performing during the generation of the sonic boom and the atmospheric profile at that time. <u>Statistics specific to focused sonic boom prediction should be developed for the ratio of observed to predicted sonic boom overpressures.</u> At this time, lacking a sufficient database to identify what values statistics should be used for focused sonic

booms, it is suggested that a conservative approach be adopted and the distribution proposed by Hershey and Higgins be used for focused sonic booms.

Figure 4-1 indicates the sensitivity of the model to the selection of the distribution of this pressure ratio. This figure shows the logarithm of the probability of breakage as a function of the nominal overpressure for a 107 ft^2 (32.6 m^2) window for two models. The first model, labeled H&H, is a direct output of the Hershey and Higgins model for a used, healthy glass window. The second model, labeled NASA, is the probability distribution which results from substituting the NASA published probability distributions for P_f/P_o derived from fighter data collected from the Edwards area and Oklahoma City. Notice that while the differences between the two models is modest at higher overpressures, at low overpressures the Hershey and Higgins statistics result in window breakage probabilities two orders of magnitude greater than those resulting from the NASA data.

The third factor, the ratio of external pressure to freefield pressure, in the load model (Equation 4-1) is treated by the Hershey and Higgins model as a random factor. Systematic factors, such as the orientation of the external face of the structure to which the load is applied, the distance of the element from the edges of the structure and the geometry of the structure immediately surrounding the element (e.g., overhangs, recessed elements, etc.), are the major sources of variability in this factor. Hence, it is more appropriate to model the effect of these variations as a contribution to the uncertainty in the probability estimates rather than as a part of the probability model.

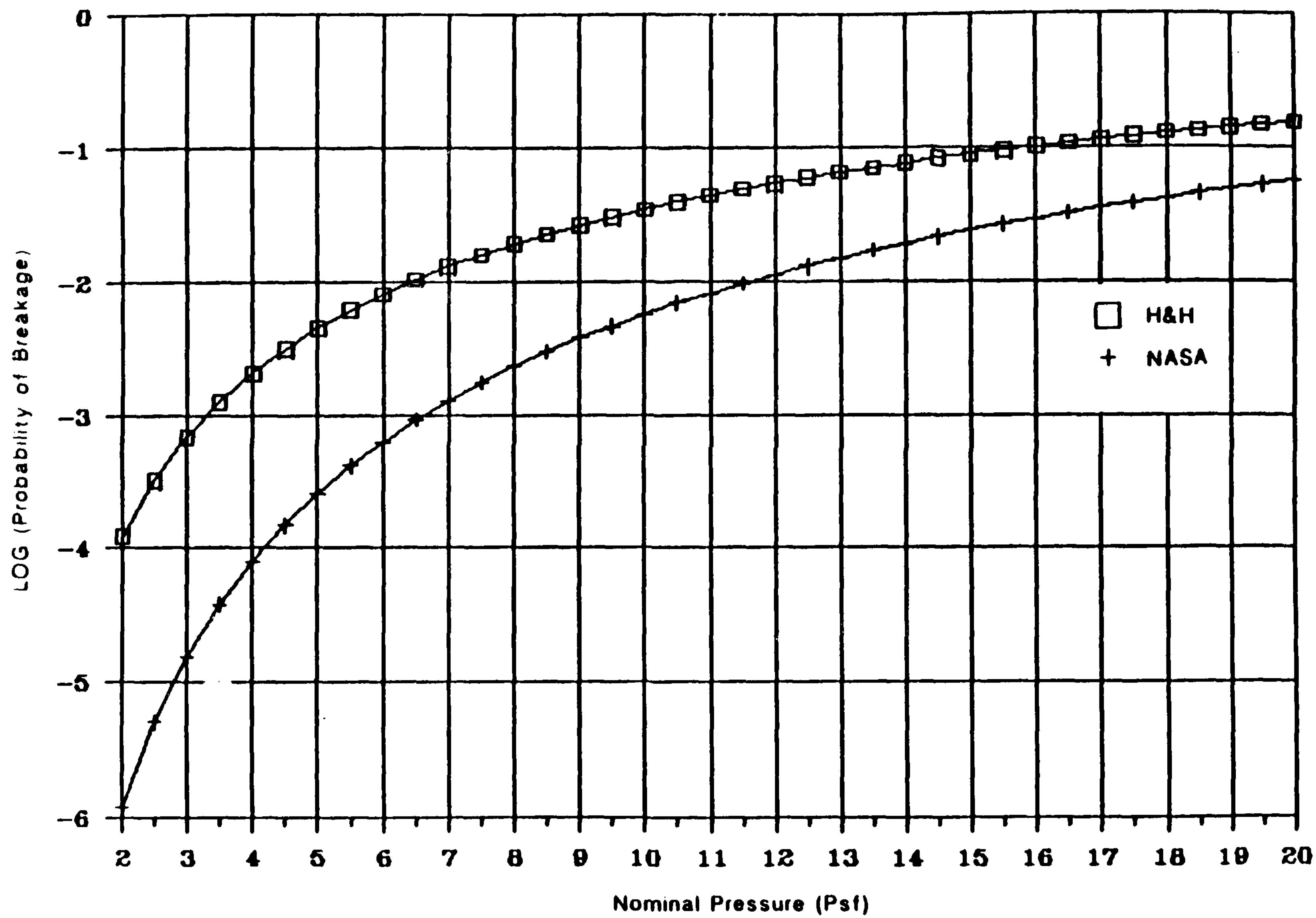

Figure 4-1. Comparison of Basic Model and NASA Model for Ratio of Measured to Predicted Freefield Over Pressure.

Figure 4-2 shows the effect of this change of perspective. For this illustration it was assumed that the uncertainty in damage estimates follows a lognormal distribution. The only source of damage estimate uncertainty considered was the uncertainty in this ratio. Illustrated are the basic Hershey/Higgins probability distribution (labeled H&H) together with three distributions which result from treating the effect of this factor as a systematic one: these three distributions are a mean (labeled MEAN), a three sigma lower bound (labeled -3 S) and a three sigma upper bound distribution (labeled +3 S). For the purpose of generating these comparisons, it was assumed that the Hershey and Higgins statistics for the ratio of external to freefield pressure were valid. These distributions correspond to the following values of the pressure ratio: mean -- 0.75, minus three sigma -- 0.18, and plus three sigma -- 3.19.

Notice that for the higher pressure region the Hershey and Higgins model agrees reasonably well with the mean distribution. In contrast to this situation, at lower, more common overpressures, there is approximately an order of magnitude difference between these two. Furthermore, notice that the range of distributions <u>due to the uncertainty in this ratio alone</u> results in six orders of magnitude variation in window breakage probability at low overpressures. This finding is consistent with the general observation that damage at low overpressures is most commonly the result of some combination of unusual "effective" loading overpressures and preboom damage or stresses.

The fourth factor is the ratio between the static stress and the peak external pressure, F. Because the appearance of this factor on the load side is exactly offset by its appearance on the capacity side of the equation its value is unimportant. Otherwise, it would be necessary to evaluate (see Equations 4-1

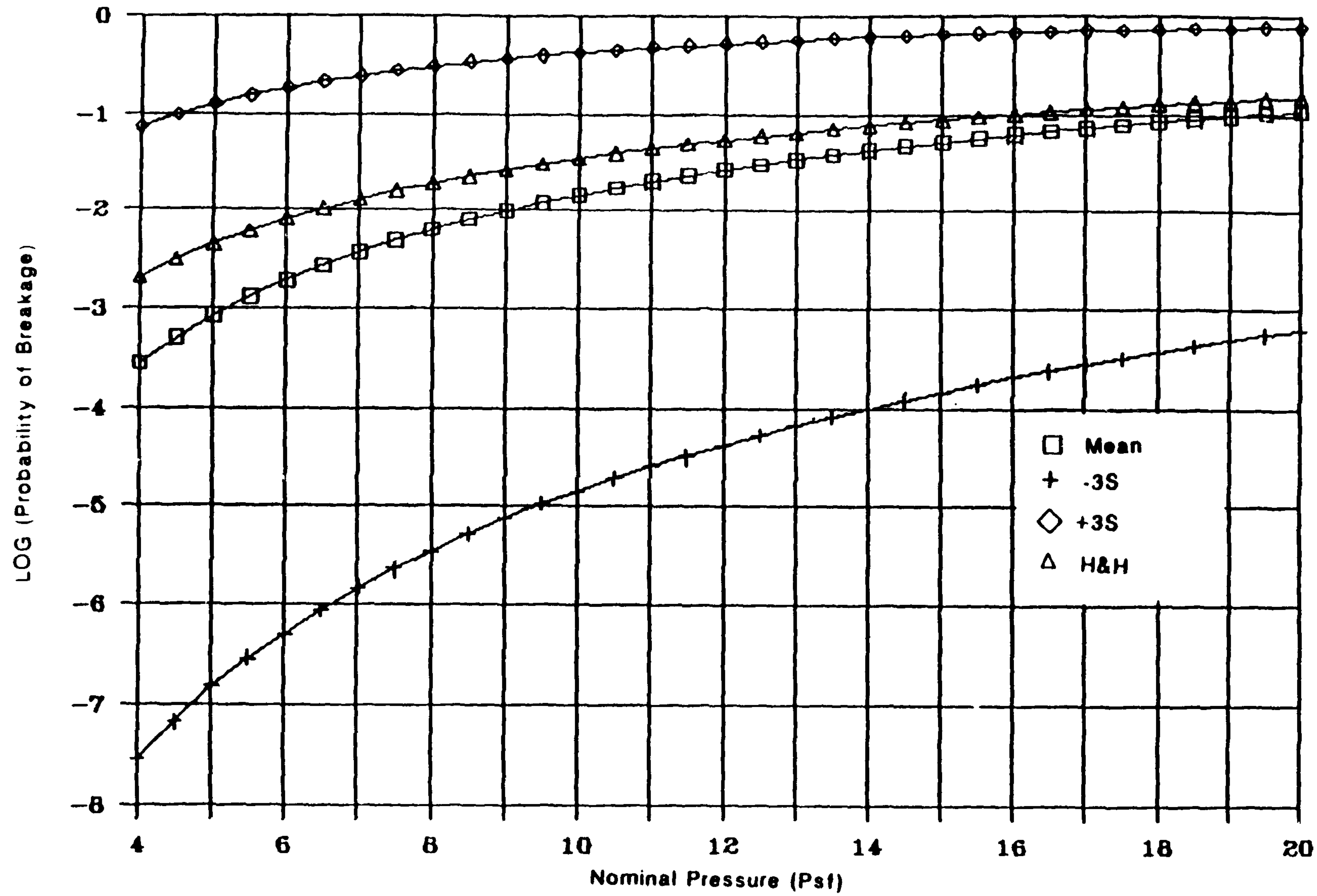

Figure 4-2. Comparison of Alternative Treatments of Variability in the Ratio of External to Freefield Over Pressure.

and 4-2) the change in this factor as a function of how a window is supported (simply supported, clamped, etc.)

The last factor in the load equation is the dynamic amplification factor, DAF. The DAF is sensitive to the fundamental frequency of the element being loaded, the loading waveform, and the duration of the loading waveform. A theoretical characterization of the fundamental frequency of windows is dependent on how they are supported. While it is known that window response is bounded by the cases of simple support and clamped support, the actual nature of the support is unique to each window. No totally satisfactory model has been proposed to characterize this response. The Hershey and Higgins approach of attempting to measure the DAFs offered a potential alternative.

Unfortunately, the large amount of uncertainty introduced into their estimates by the procedures employed make these statistics of questionable value. A significant variation of the loading waveforms was present in their data and for five out of seven windows analyzed P_e had to be estimated. Hershey and Higgins developed their statistics from the White Sands and Edwards AFB field tests. The White Sands tests involved F-104 and B-58 aircraft, generally flying at lower than normal altitudes to create high overpressures. Hershey and Higgins employed the freefield overpressure measurements together with measurements of external pressures at the center of the walls of a structure designated as W4. For each overflight the direction of the flight vector to the nearest 45 degrees, the freefield overpressure and the external overpressures were recorded. They performed a regression analysis to relate $\mathrm{Log}(P_e/P_f)$ to the cosine of these discrete headings.

In addition, two windows were instrumented with strain gauges. Gauges were located at the center of the windows. The maximum stress was derived from the measured strains. Using the measured value of P_e and the geometry factor, F, DAFs could be directly calculated.

An additional set of DAF statistics was developed for five windows at Edwards Air Force Base using measured strains, measured freefield pressures and the regression relationship between aircraft heading and $Log(P_e/P_f)$.

The Edwards AFB tests involve overflights of B-58, XB-70, F 104 and SR-71 aircraft (4). These overflights ranged from about 18,000 ft at typical speeds of Mach 1.3 to over 60,000 ft at speeds up to Mach 2.5. Significantly, the mix of testing at both White Sands and Edwards included a wide variation in duration of the loading waveforms. Consequently, the sample of calculated DAFs is not a good basis for calculating DAFs for these windows. For the Edwards windows the uncertainty was further increased by the uncertainty resulting from using the regression equation to calculate the external pressures and the additional uncertainty resulting from the discretizations based on 45 degree heading increments used in calculating this equation.

Under these circumstances, it seems prudent to calculate DAFs theoretically for both typical N-waves and focused sonic boom waveforms. Since no strong evidence exists for any particular probability distribution for the DAFs, no comment can be made of the suitability of the lognormal distribution adopted by Hershey and Higgins. Random factors will then be used to address deviations from these idealized waveforms and deviations of the level of damping in an affected element from its nominal value. A systematic factor contributing to the uncertainty in

the estimates so derived will be the type of support that the window has.

Figures 4-3 and 4-4 illustrate a typical N-wave and a typical focused sonic boom waveform. Various characteristics of the waveforms have been labeled on these figures to aid the reader in understanding the subsequent material regarding the sensitivity of DAF curves to changes in waveforms.

Normalized DAF curves are shown in Figure 4-5 for N-waves for three levels of damping. The case of no damping provides a reference case, the 2% of critical damping is representative of windows and the 4% of critical damping is typical of plaster walls. Notice that for all three curves, as the ratio between wave duration and natural period increases, the variation in DAF decreases. Moreover, as level of damping increases the ratio for which the DAF stabilizes decreases. Figures 4-6 through 4-8 (7) illustrate the sensitivity of N-wave DAF curves to deviations from a symmetrical N-wave for an undamped system. Each figure treats one type of variation in waveform. Figure 4-6 addresses asymmetry, Figure 4-7 shows the effect of finite rise times, and Figure 4-8 shows the effect of "spiked" waveforms.

Figures 4-9 through 4-11 depict the normalized DAF curves for focused sonic boom waves for an undamped oscillator, for 2% of critical damping and for 4% of critical damping respectively. Comparing these figures with Figure 4-5 (DAF for an N-wave) shows clearly that the focused sonic boom produces smaller DAFs than the N-wave and that the maximum DAF produce by a focused wave occurs for a higher period ratio (approximately eight) than for an N-wave (approximately eight-tenths).

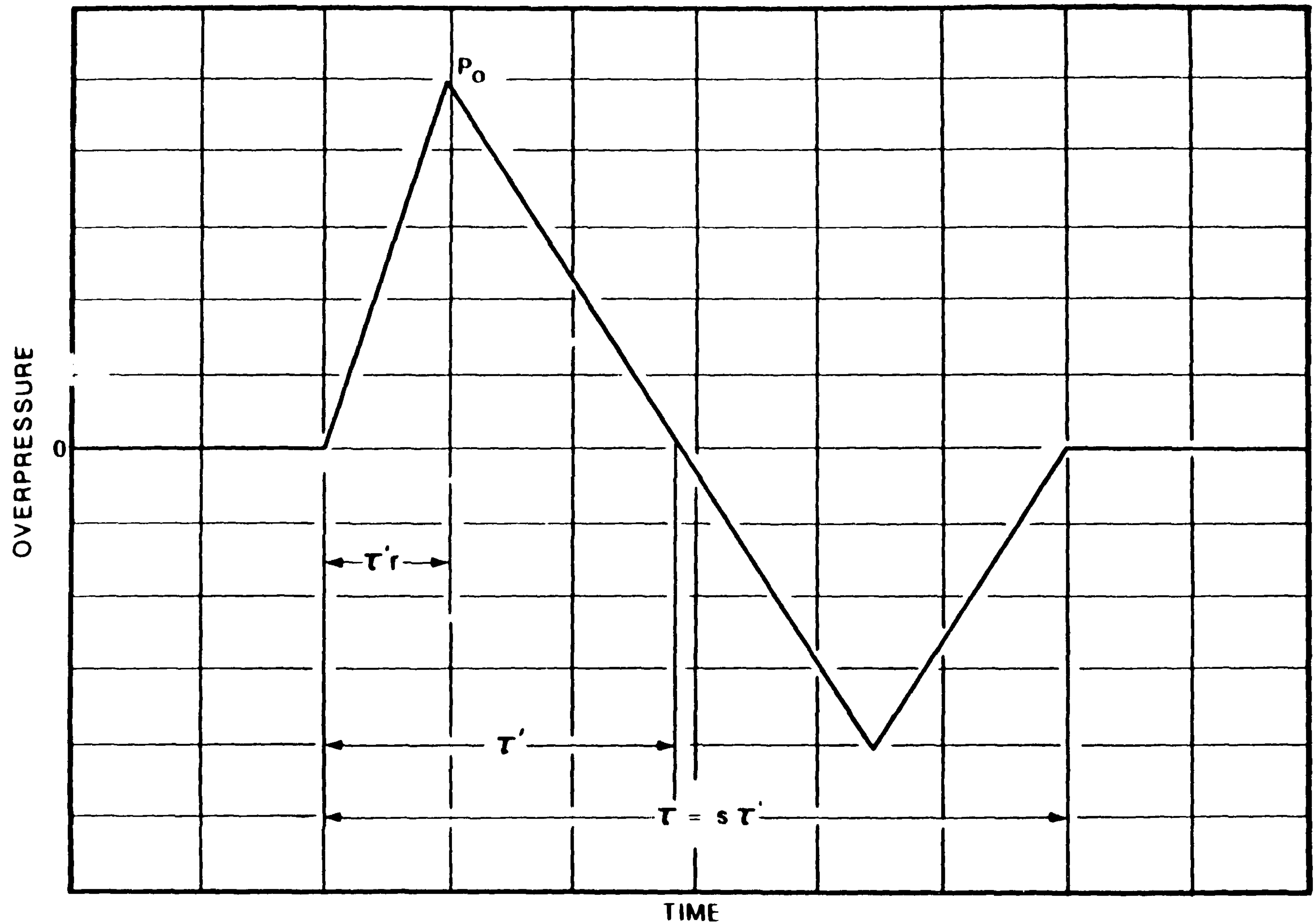

Figure 4-3a. Typical Sonic Boom (N-wave) Form.

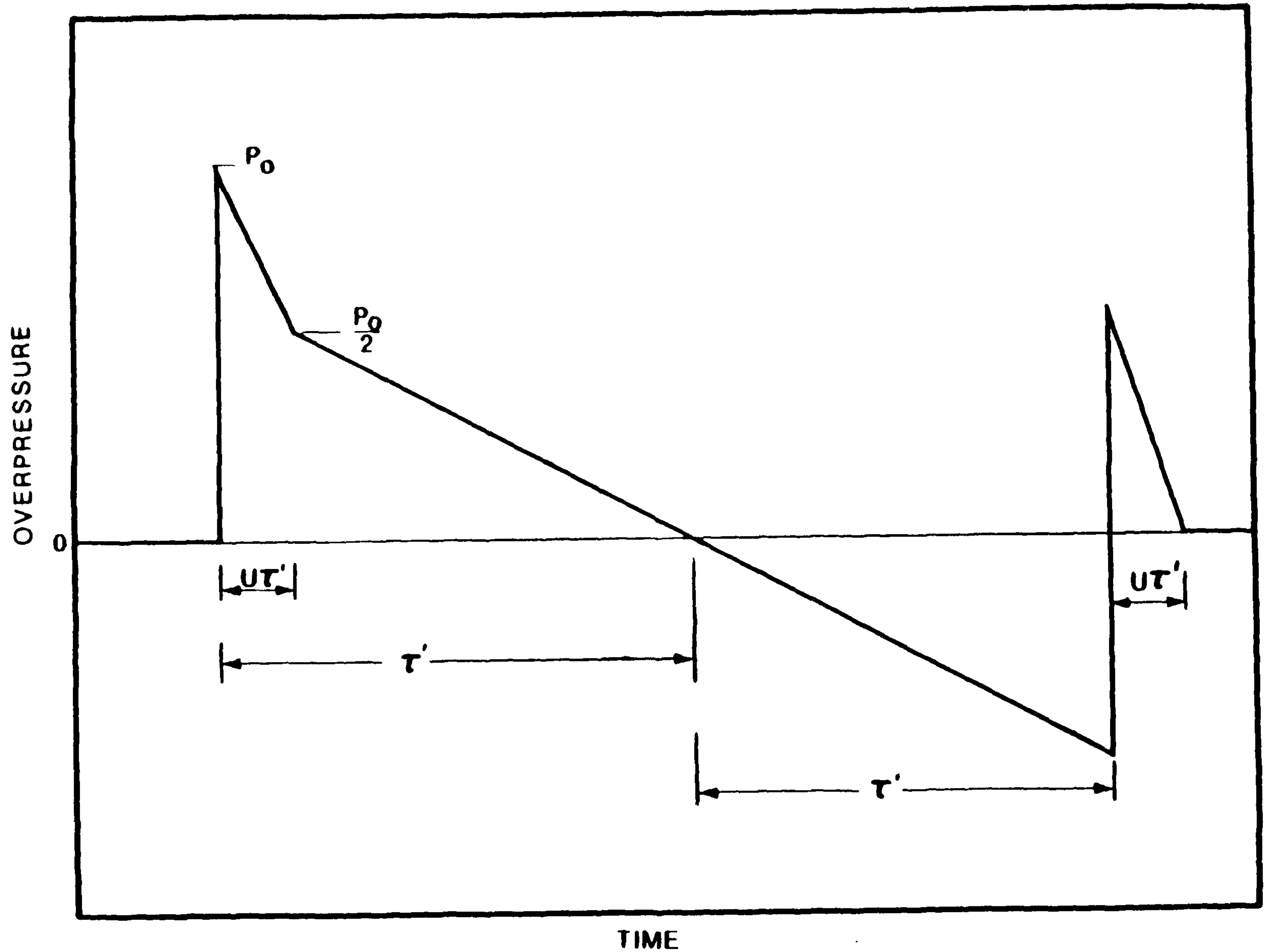

Figure 4-3b. General Spiked N-Wave Form.

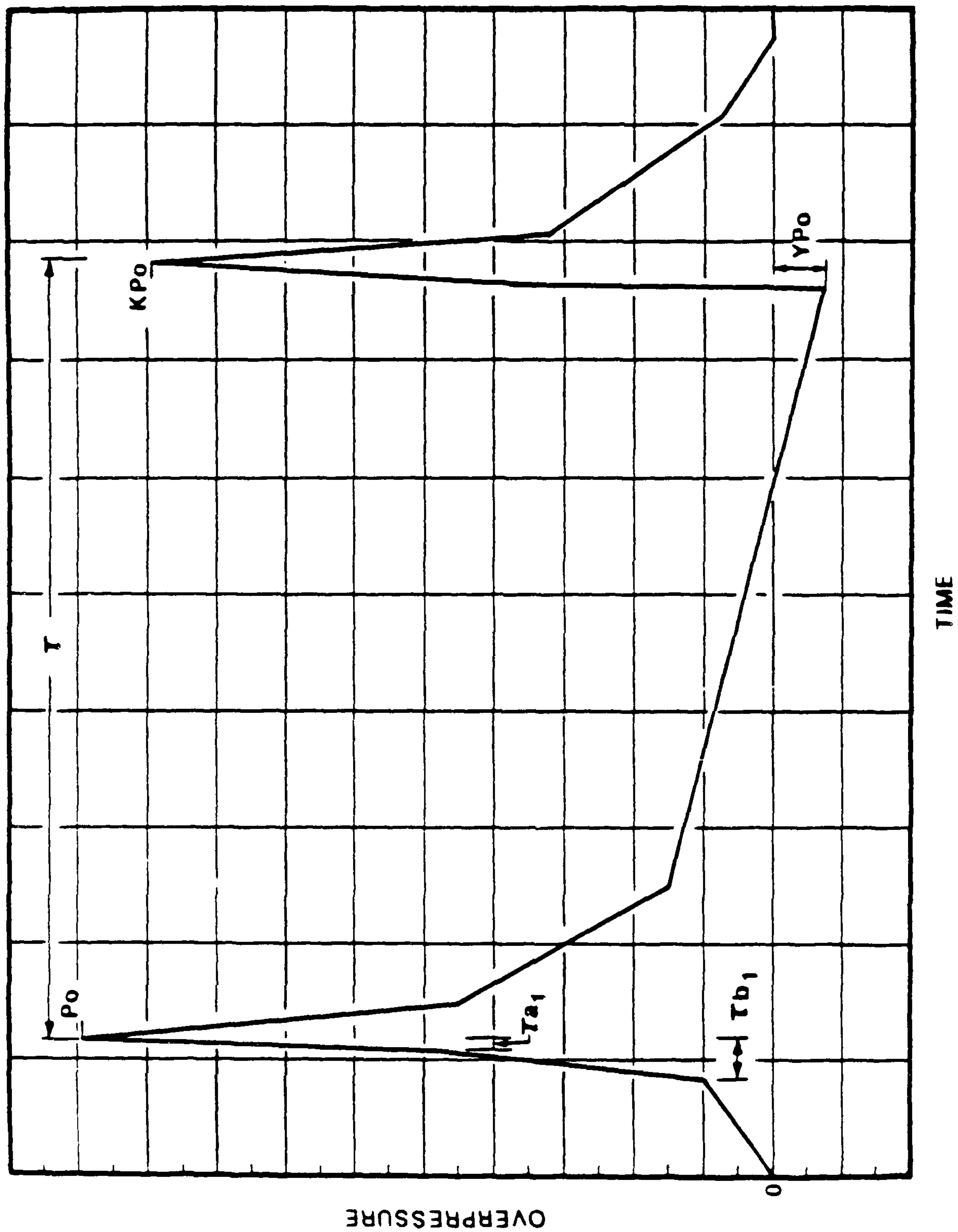

Figure 4-4. Typical Focused Sonic Boom Wave Form.

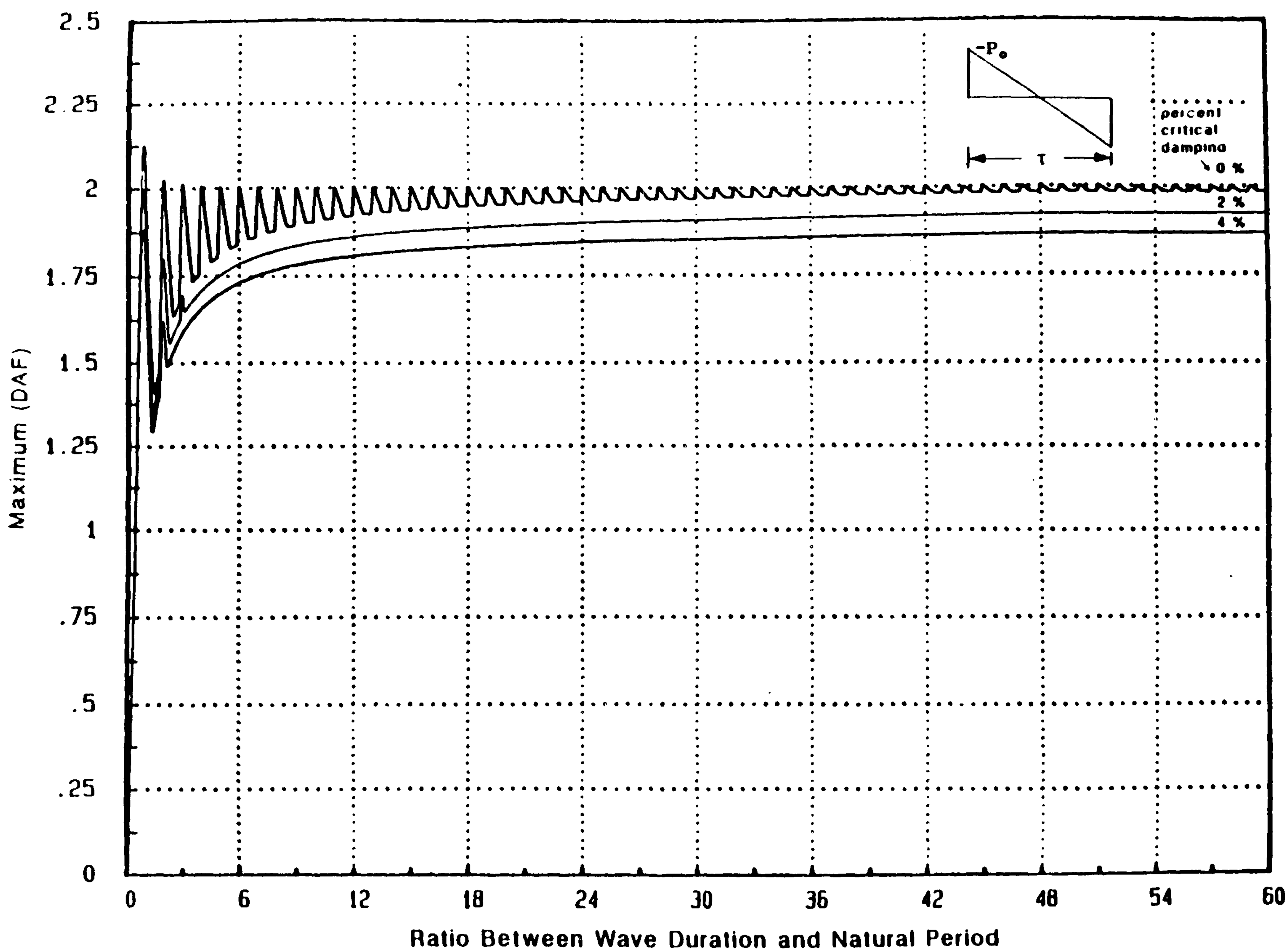

Figure 4-5. Variation of Maximum (DAF) of SDOF System Due to N-Wave.

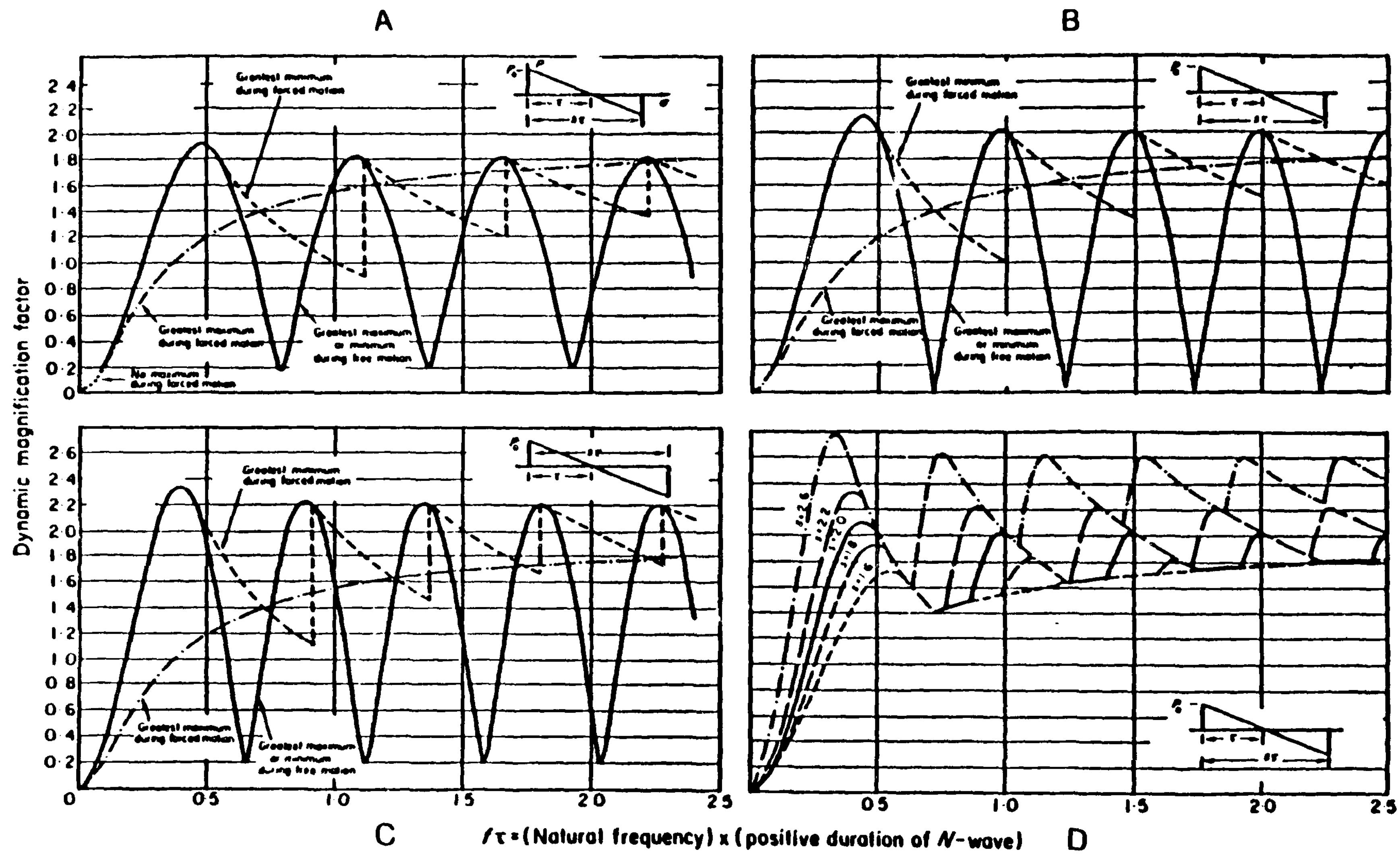

Figure 4-6. Sensitivity of N-Wave Dynamic Amplification (Magnification) Factor To Asymmetry for An Undamped System. (A. S=1.8, B: S=2.0, C: S=2.2, D: Summary) (Crocker & Hudson, 1969)

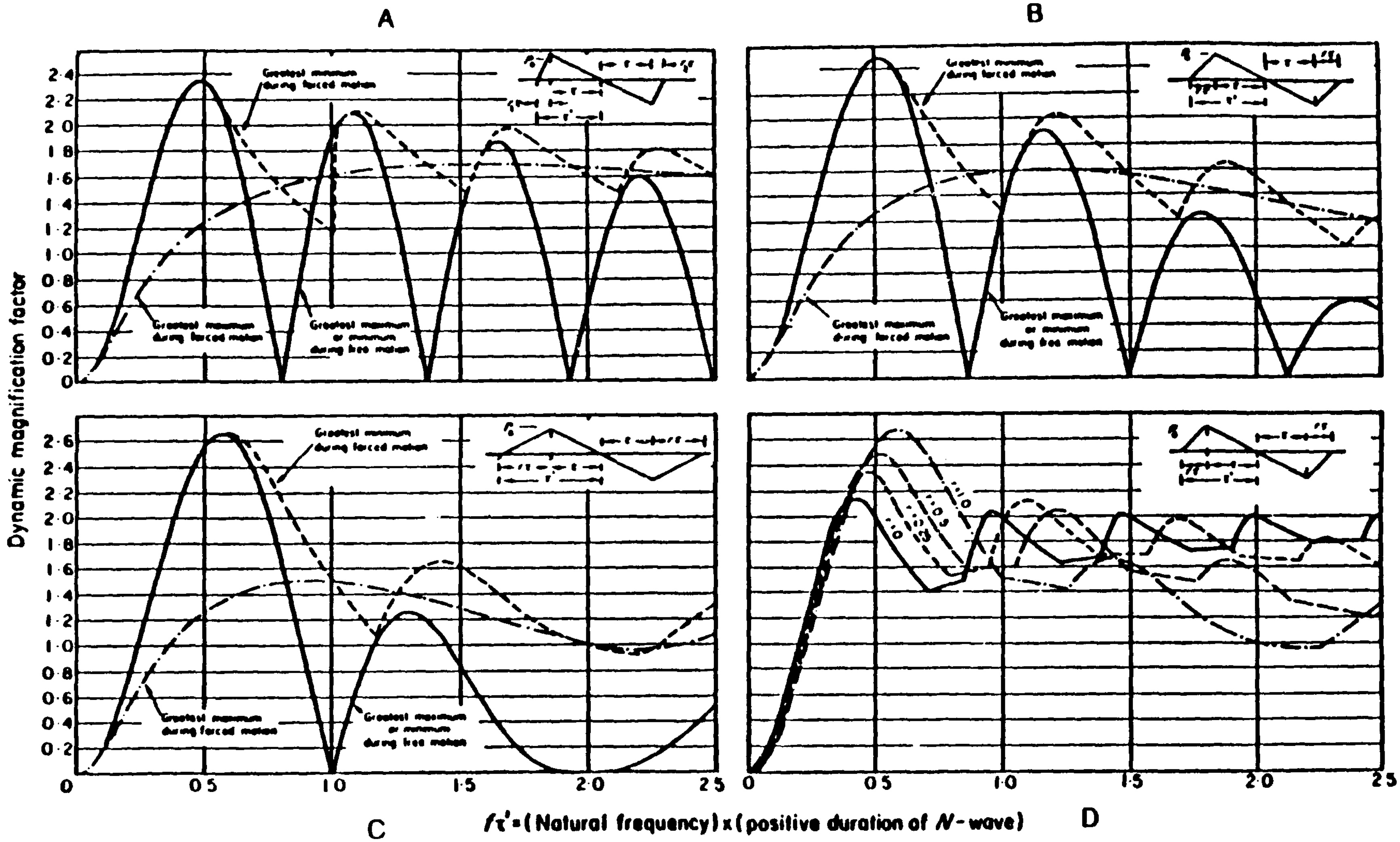

Figure 4-7. Sensitivity of N-Wave Dynamic Amplification (Magnification) Factor To Rise Time for an Undamped System. (A: r=0.25, B: r=0.50, C: r=1.00, D: Summary). (Crocker & Hudson, 1969)

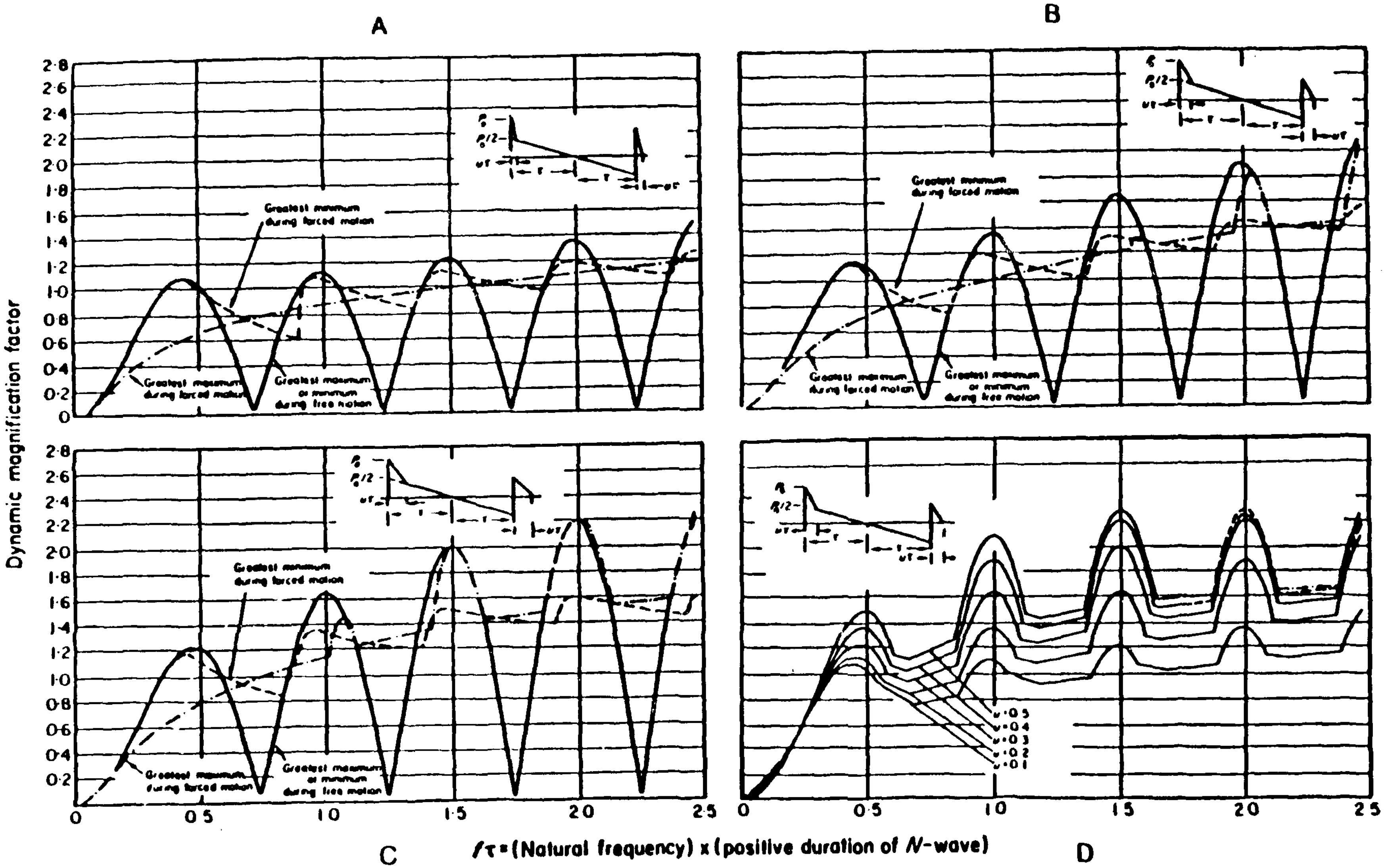

Figure 4-8. Sensitivity of N-Wave Dynamic Amplification (Magnification) Factor To Spiked Waveform for an Undamped System. (Crocker & Hudson, 1969)
(A u=0.1, B: u=0.2, C: u=0.3, D: Summary)

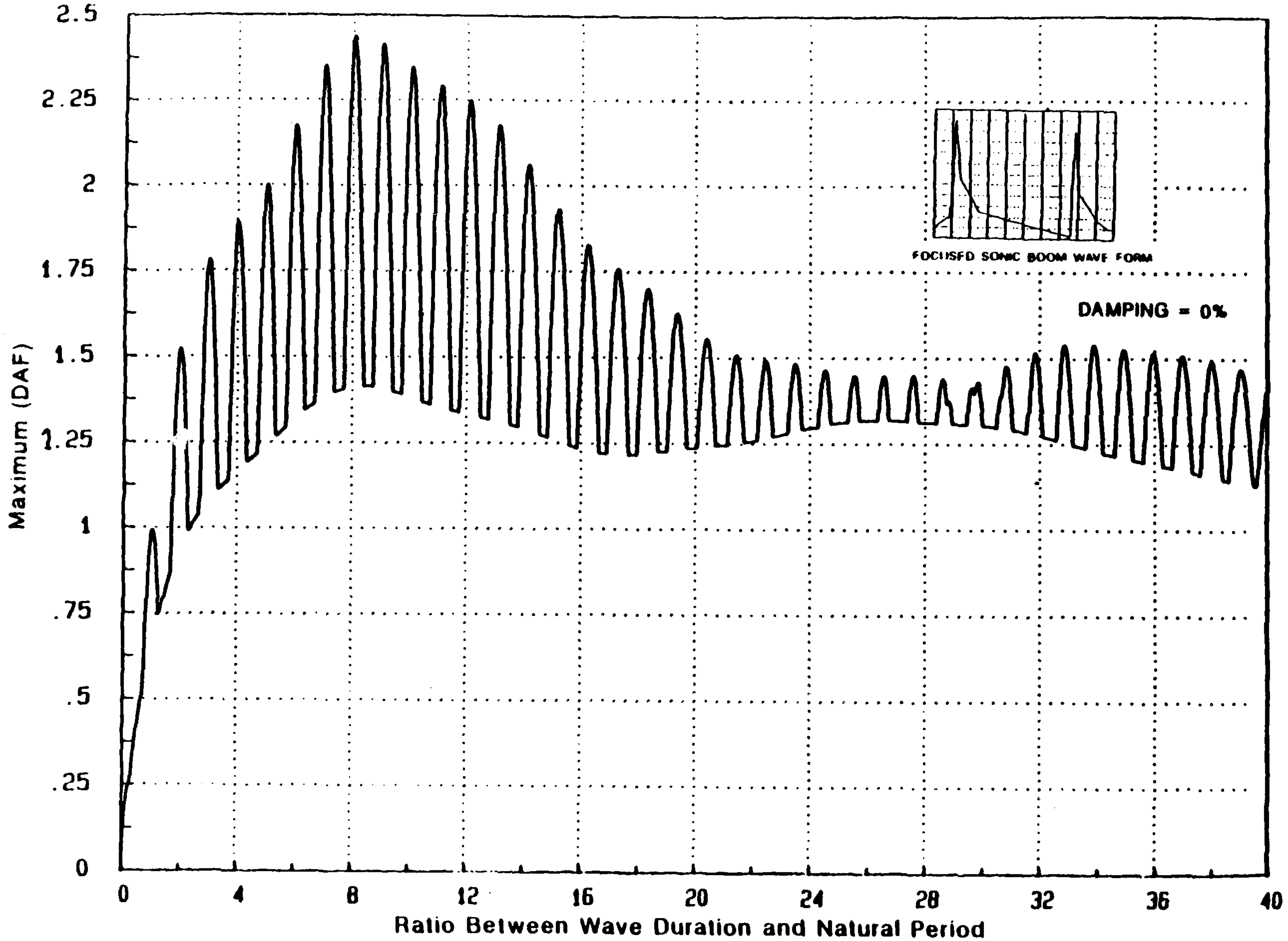

Figure 4-9. Maximum (DAF) of Undamped SDOF System Due to Focused Sonic Boom.

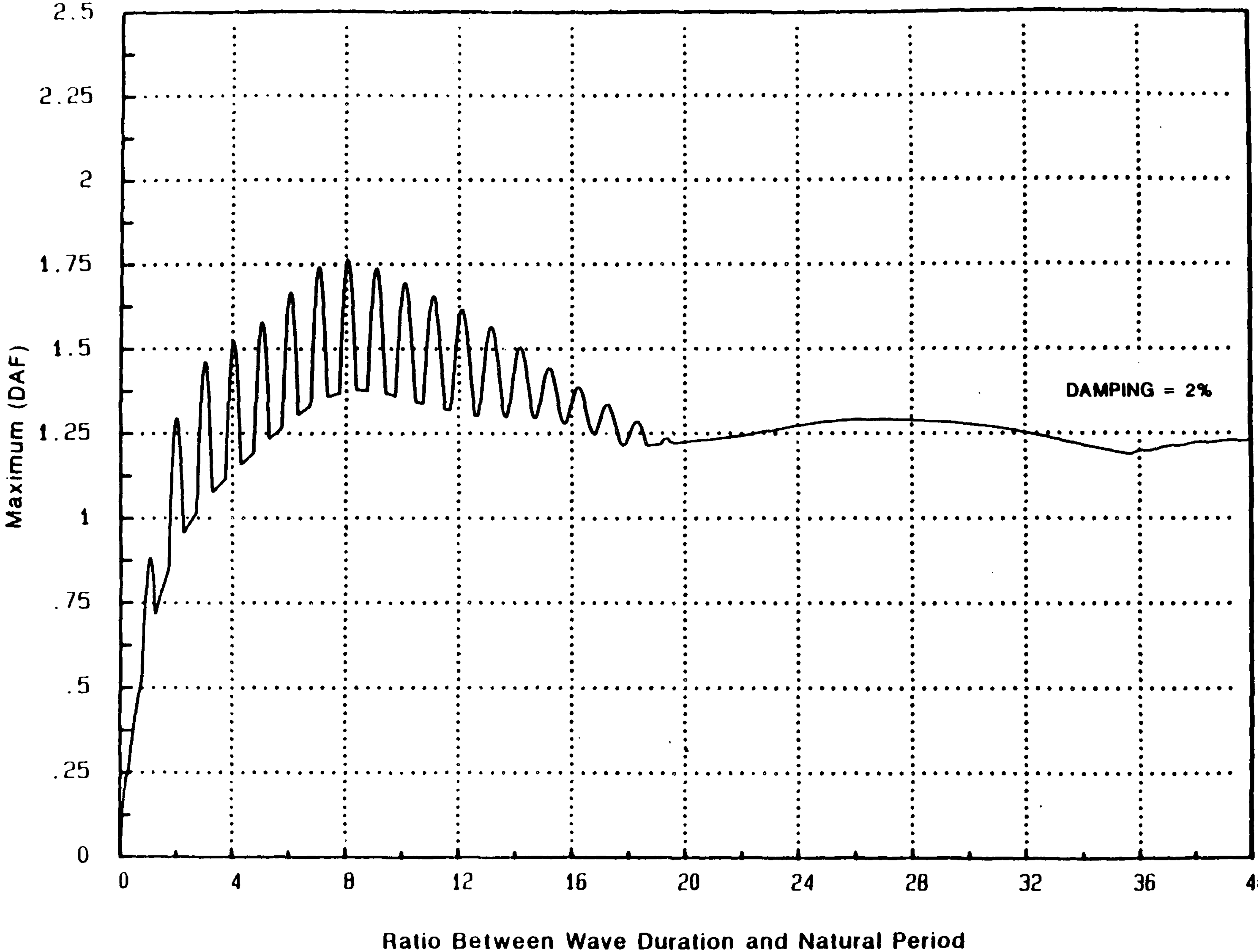

Figure 4-10. Maximum (DAF) of SDOF System Due to Focused Sonic Boom (2% Damping).

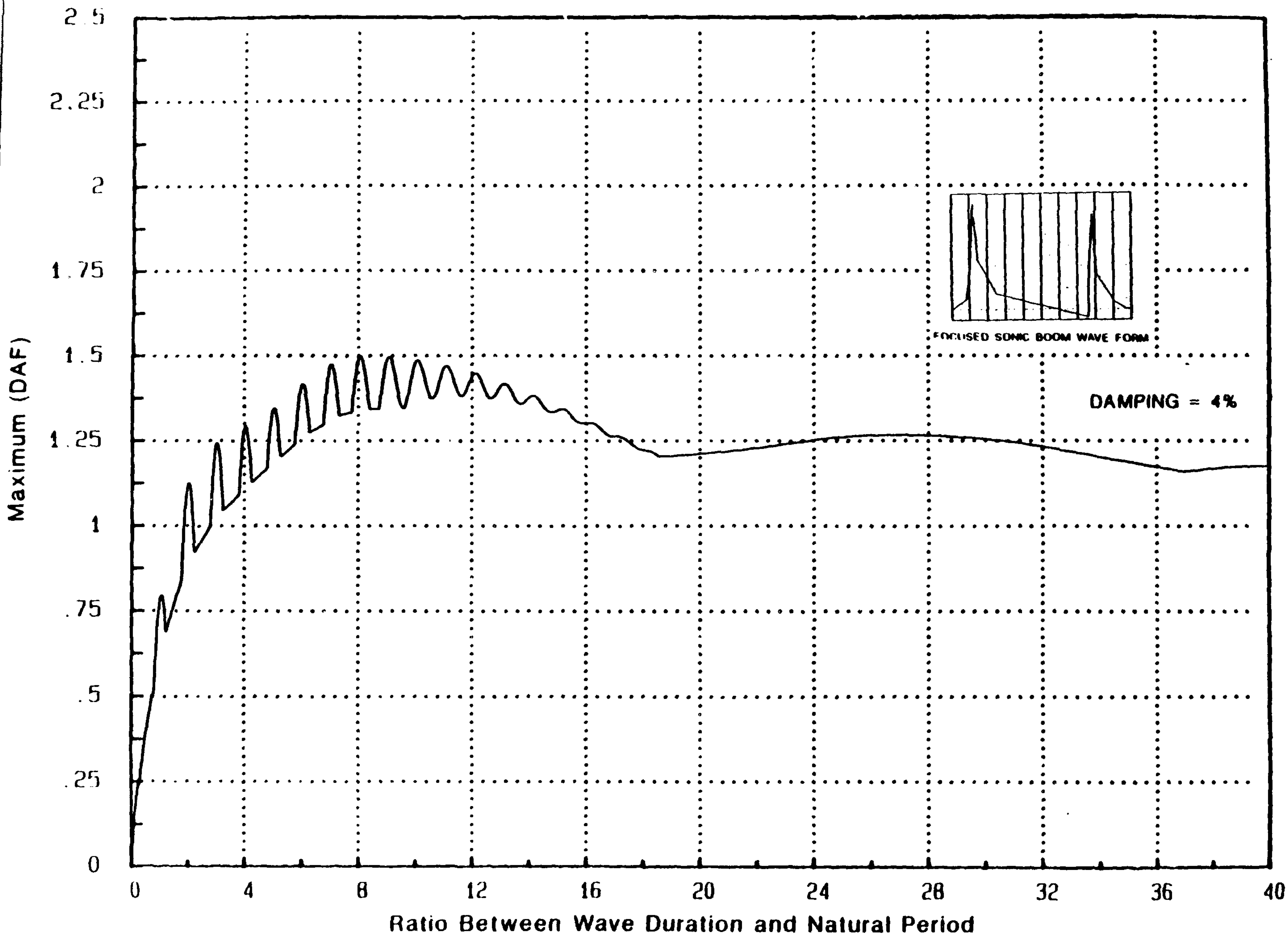

Figure 4-11. Variation of Maximum (DAF) of SDOF System Due to Focused Sonic Boom (4% DAMPING).

Figures 4-12 through 4-14 illustrate the sensitivity of the DAF curves for focused waves to variations in the waveform. (The figures address the case of 2% damping.) Figure 4-12 shows the effect of changing the relative amplitude of the two positive peaks where K is the ratio of the amplitude of the second peak to that of the first peak. Figure 4-13 shows the effect of varying the width of the peaks. (These are parameterized by the variables a_1 and b_1 which were defined in Figure 4-4). Figure 4-14 shows the effect of varying the amplitude of the negative phase of the wave where Y is the ratio of the amplitude of the negative phase to the amplitude of the first positive peak. Among the three variations in waveform evaluated it is clear from these figures that the DAF curves are most sensitive to the change in the amplitude of the negative phase of the focused sonic boom waves.

Figure 4-15 compares the damage curve from the baseline model (labeled H&H) for a 107 ft^2 (32.6 m^2) window with those resulting from adjusting the DAF statistics (no other adjustments to the baseline model were made for the purpose of generating these comparisons). The wave duration selected was that typical of fighter aircraft. The results are shown for both an N-wave as well as a focused wave. Figure 4-16 presents the same type of comparison for a 0.84 ft^2 (0.256 m^2) window. Notice that, as expected, the damage predictions of the baseline model are higher than those for either wave type. Moreover, while focused sonic booms result in higher overpressures than N-waves, for a given overpressure the damage probability is <u>higher</u> for an N-wave than for a focused wave. The capacity model has two factors. As previously indicated the factor F in this model is of no concern because of its compensating appearance in the load model. The second factor is the breaking strength of the plate.

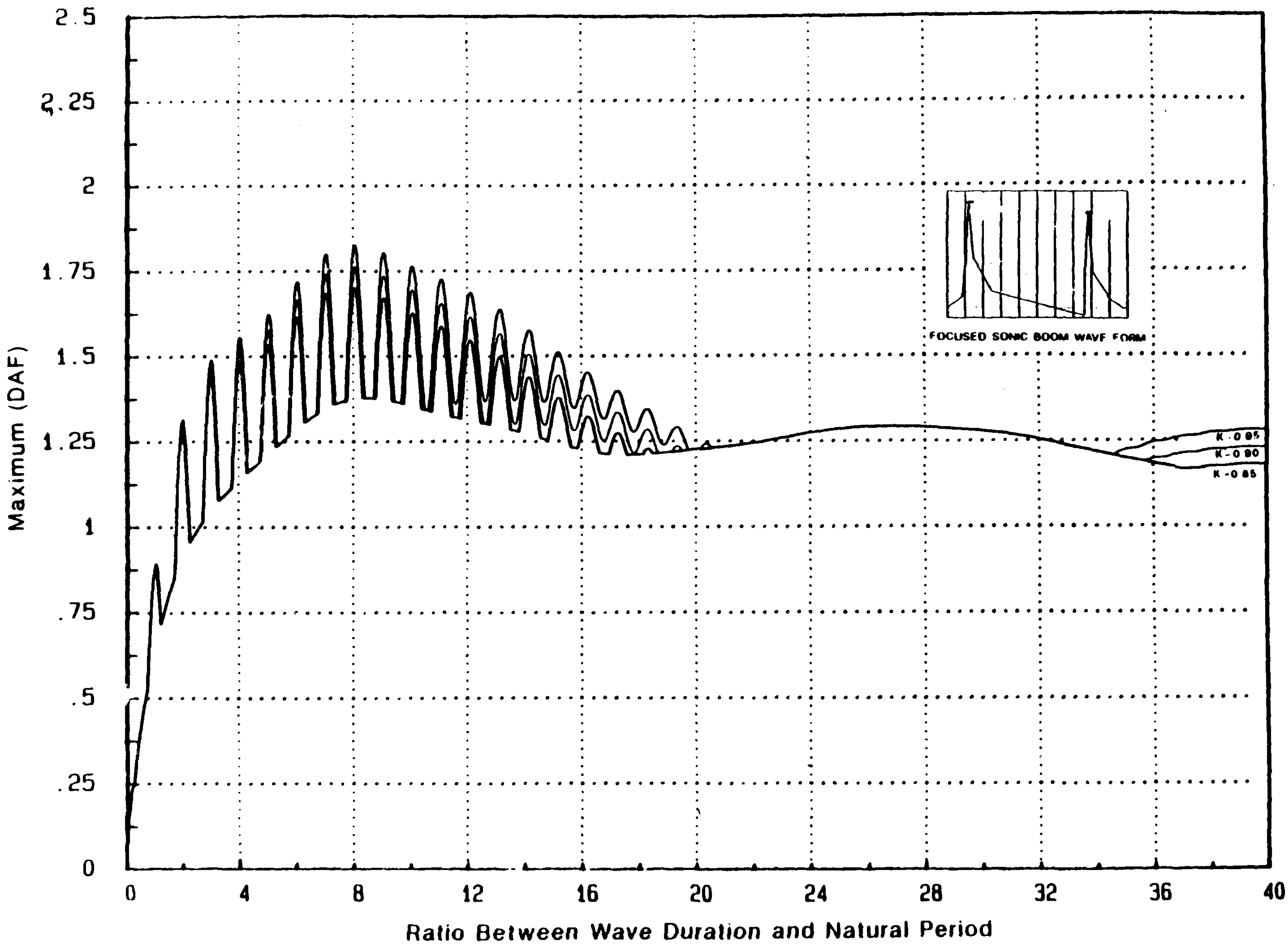

Figure 4-12. Sensitivity of Maximum (DAF) of SDOF System to Ratio of Amplitude of Peaks.

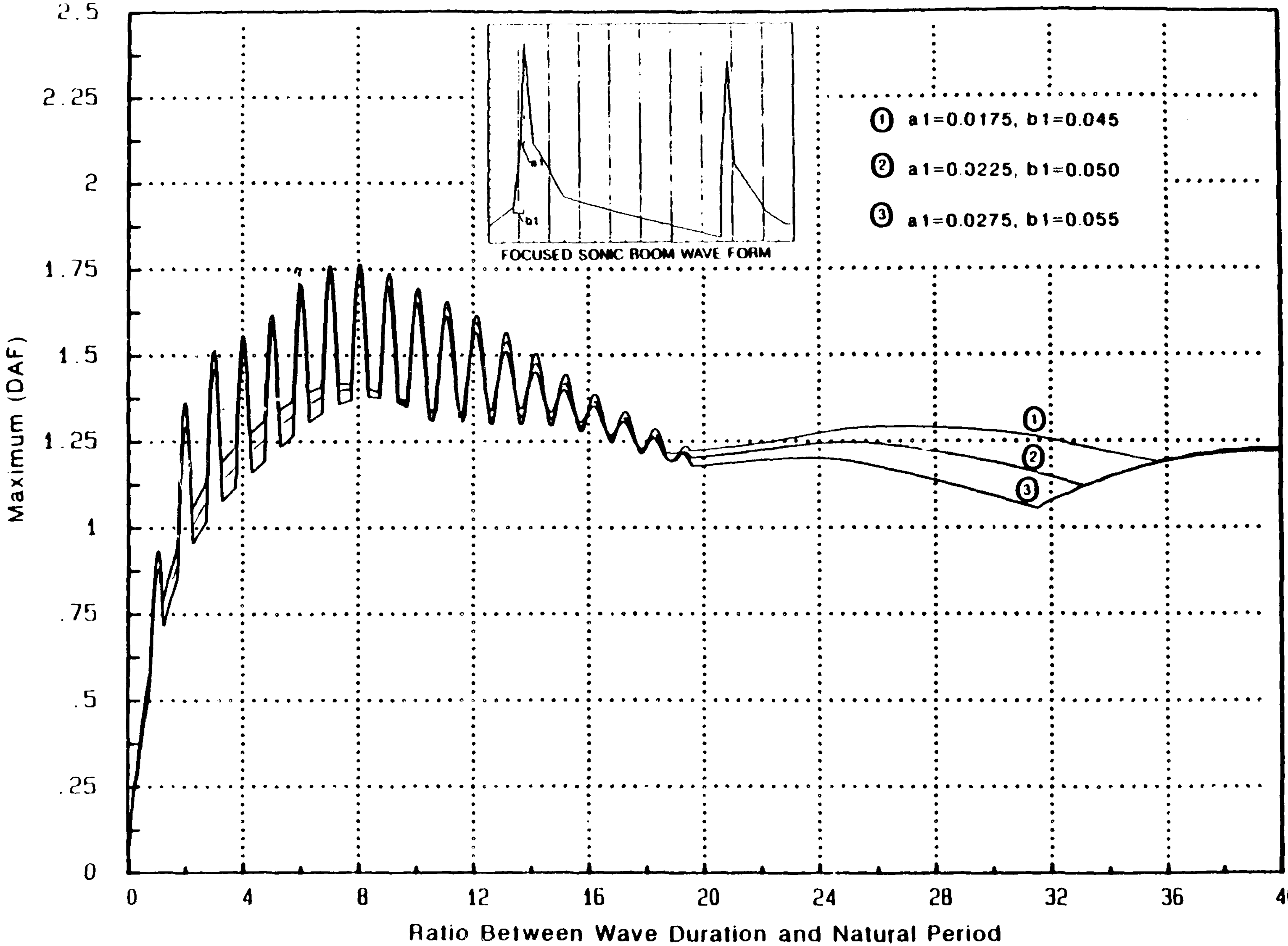

Figure 4-13. Sensitivity of Maximum (DAF) of SDOF System to Width of First Peak.

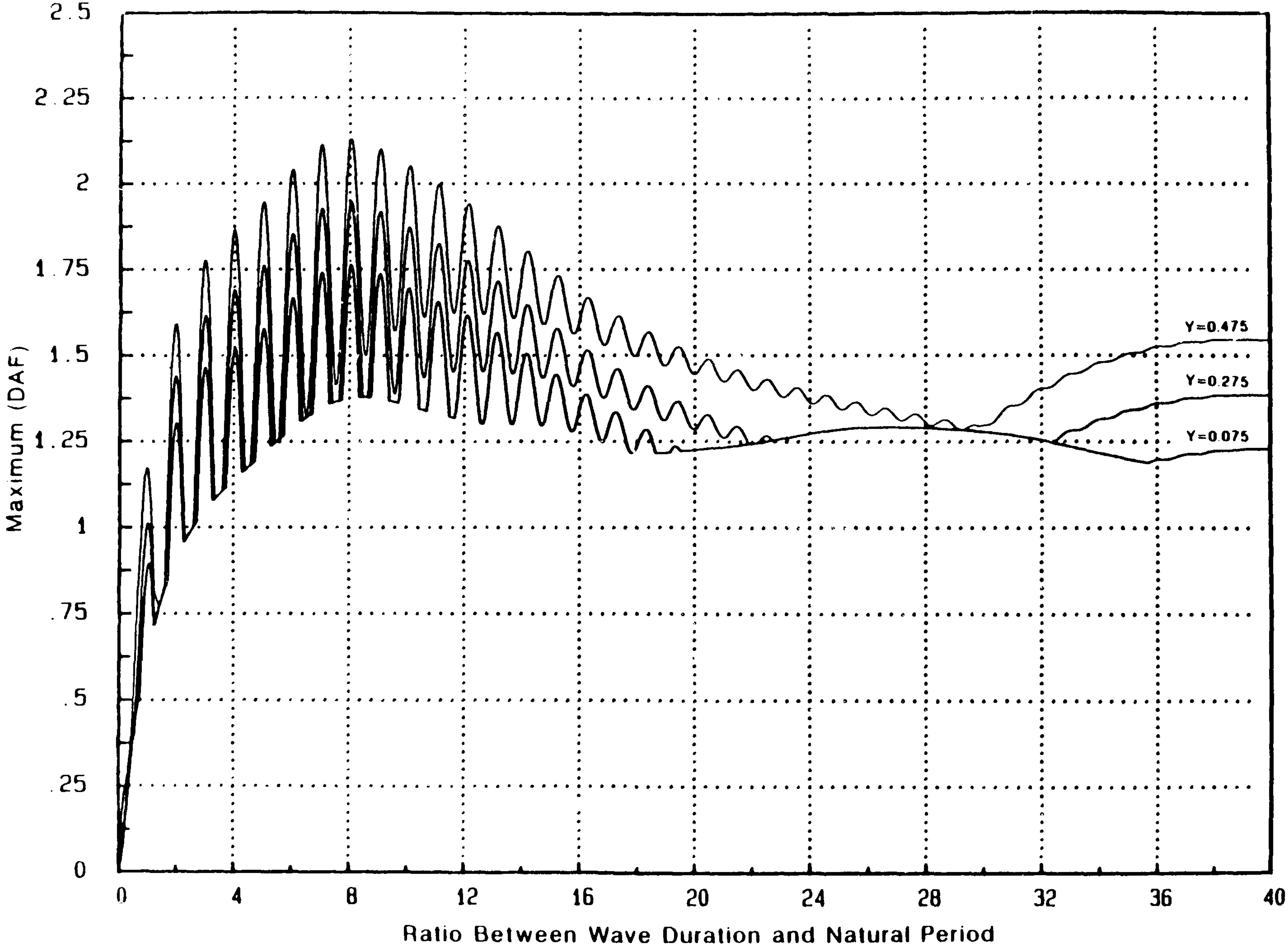

Figure 4-14. Sensitivity of Maximum (DAF) of SDOF System to Amplitude of Negative Peak.

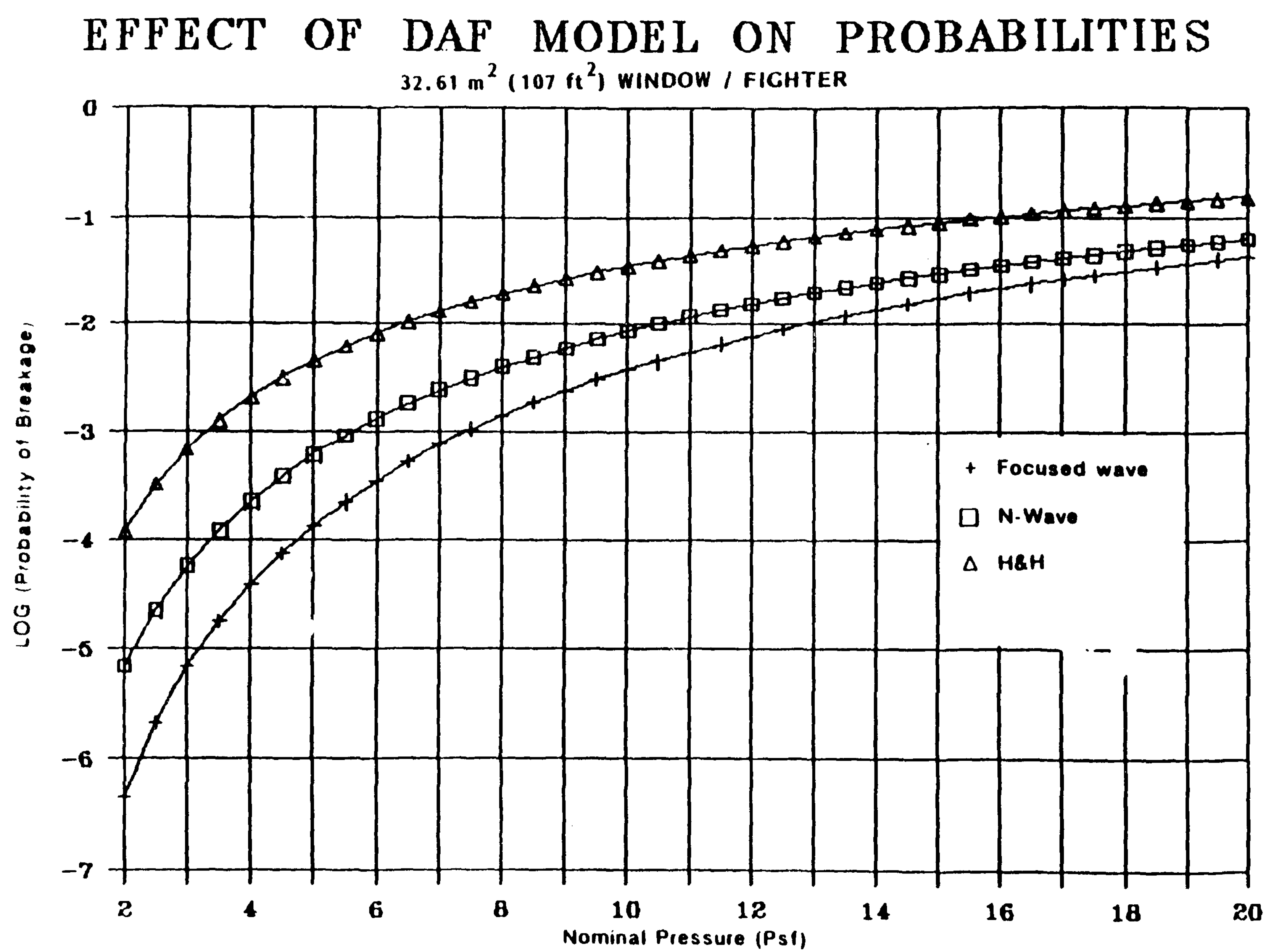

Figure 4-15. Sensitivity of Baseline Window Damage Probability Model to DAF Statistics

(32.61 m^2 (107 ft^2) Window, Load Duration = 100 msec).

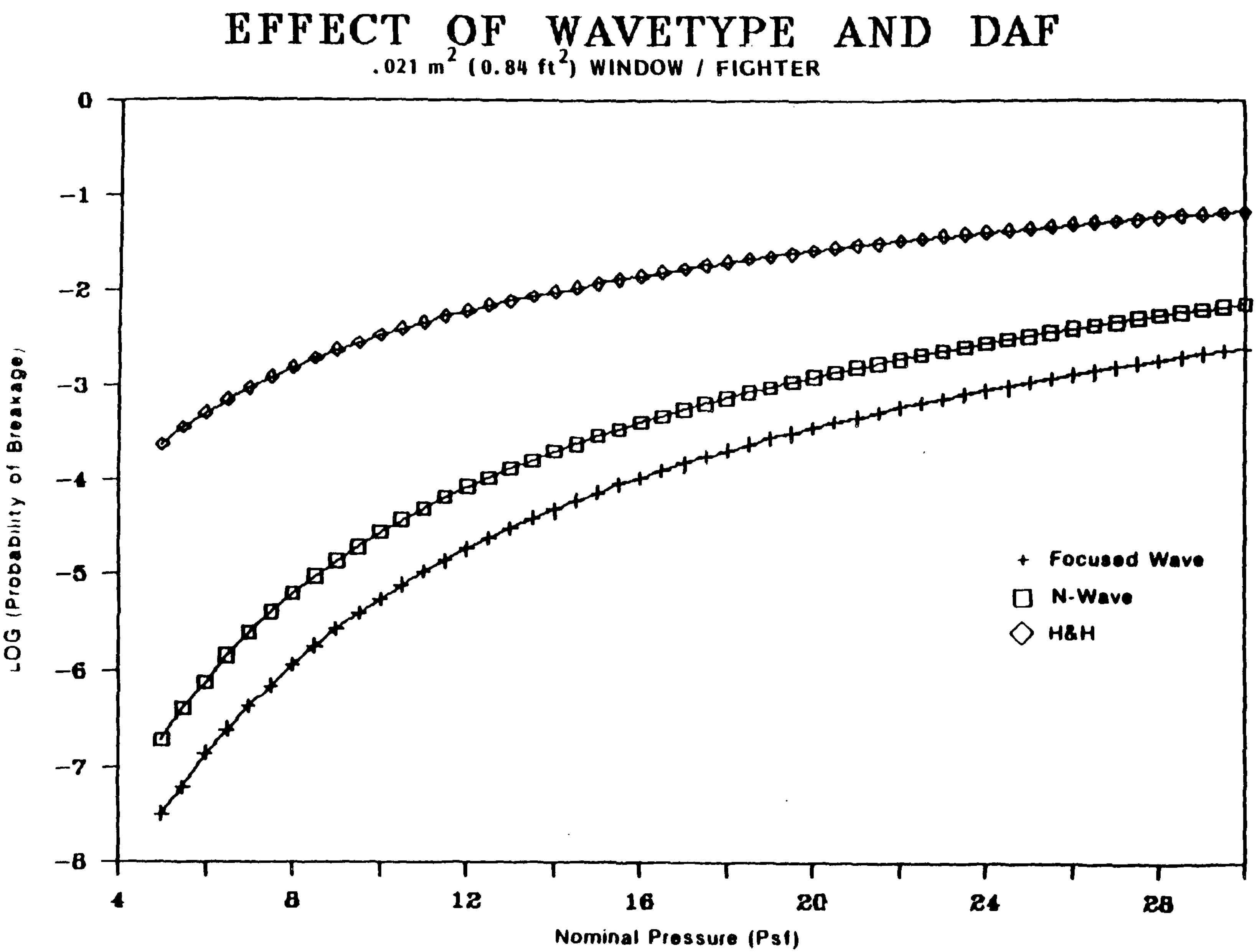

Figure 4-16. Sensitivity of Baseline Window Damage Probability Model to Wave Type & DAF ($.021\ m^2$ ($0.84\ ft^2$) Window, Wave Duration = 100 msec).

The strength of glass plates, as recommended by glass manufacturers, is described in terms of a constant failure load, specifically pressure. The failure criterion is dependent on the dimensions of the plate and the duration of the load. The industry standard refers to the failure pressure as a constant, uniform 60-sec pressure. Specification of a standard load duration is required because glass exhibits static fatigue in which the strength of the glass decreases as the duration of the load increases.

A recent study conducted at Texas Tech (10) evaluated the (60-sec loading) breaking pressures of samples of healthy, used glass from a number of locations. These data provide an opportunity to compare the effects of weathering and the resulting surface flaws on glass strength with those of the Hershey and Higgins model. The useful published data were for windows removed for testing from buildings in Texas and Oklahoma. The typical window age was 20 years. These results compared favorably with the Libbey-Owens-Ford formula for the breaking pressures of new glass and the assumption made by Hershey and Higgins that there was a mean reduction in strength from new to used glass of a factor of 2. Moreover, the variance of the reported distributions was highly consistent with that reported by Hershey and Higgins. It should noted, however, that the reported reduction in strength ranged from 40% to 60%. Furthermore, there is no indication that the full range in strength reduction has been defined by these tests.

The Texas Tech results suggest that the exact strength reduction from new to used glass is dependent on location-dependent variables. (Indeed, two sets of samples taken from the same building showed virtually the same strength reductions.) However, since the Texas Tech tests are not extensive enough to define the environmental factors which govern the strength reduction of used glass, it can only be

treated as a factor which contributes to the uncertainty of the results. Figure 4-17 shows the result of varying the strength reduction factor on breakage probability.

Five curves are shown in this figure: the distribution associated with the Hershey and Higgins assumption of a 50% reduction in mean breaking pressure of the used glass as compared to the new glass and four curves associated with alternative assumptions in this strength reduction factor.

The following formula furnished by Pittsburgh Plate Glass provides a scaling factor, S, from the standardized 60-sec loading breaking pressures to a load of duration t (measured in seconds):

$$S = 1.37\ t^{-0.0653} \qquad (4\text{-}3)$$

We propose to use the factor, S, given by the Equation 4-3 instead of the factor of two adopted by Hershey and Higgins. Figures 4-18 through 4-20 display damage probability curves based upon the use of Equation 4-3 to adjust capacity for load durations of 50 ms, 100 ms, 200 ms, and 300 ms, as well as the baseline model which uses a constant factor of 2 for all sonic booms. These illustrations show the effect of only the change in strength caused by variation in load duration; it does <u>not</u> show any effect on the DAF. The remainder of the distribution is based on the standard Hershey and Higgins model. In this figure the distribution associated with the baseline assumptions presented by Hershey and Higgins (the factor of 2) is labeled H&H. The other distributions, derived from the formula cited, are labeled according to the duration of the assumed sonic boom wave. Unlike the load parameters for which the Hershey and Higgins model resulted in damage estimates which were too <u>high</u>, the duration factor in their capacity model results in damage

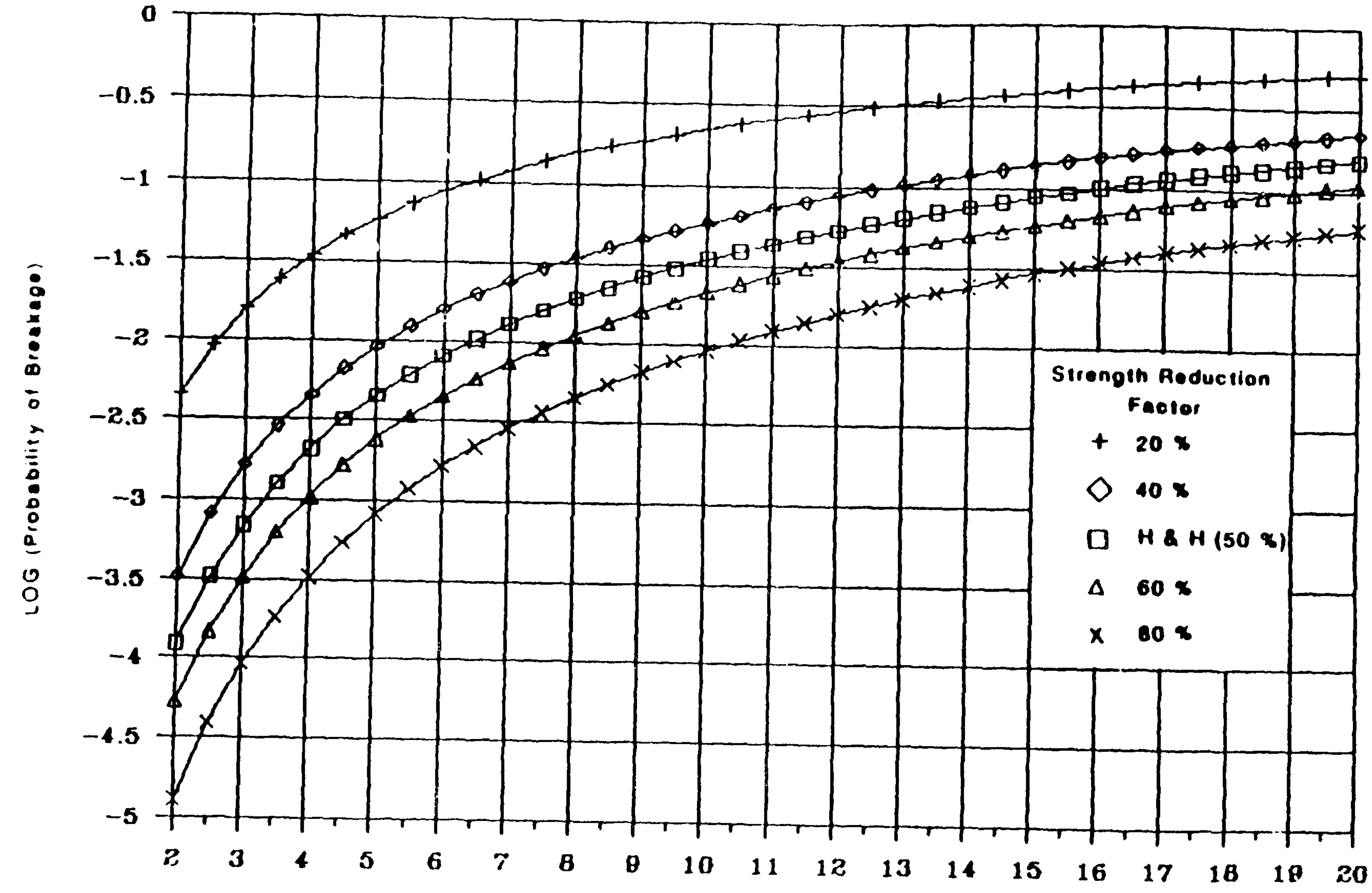

Figure 4-17. Sensitivity of Breakage Probability to the Strength Reduction Factor ($32.61\ m^2$ ($107\ ft^2$) Window).

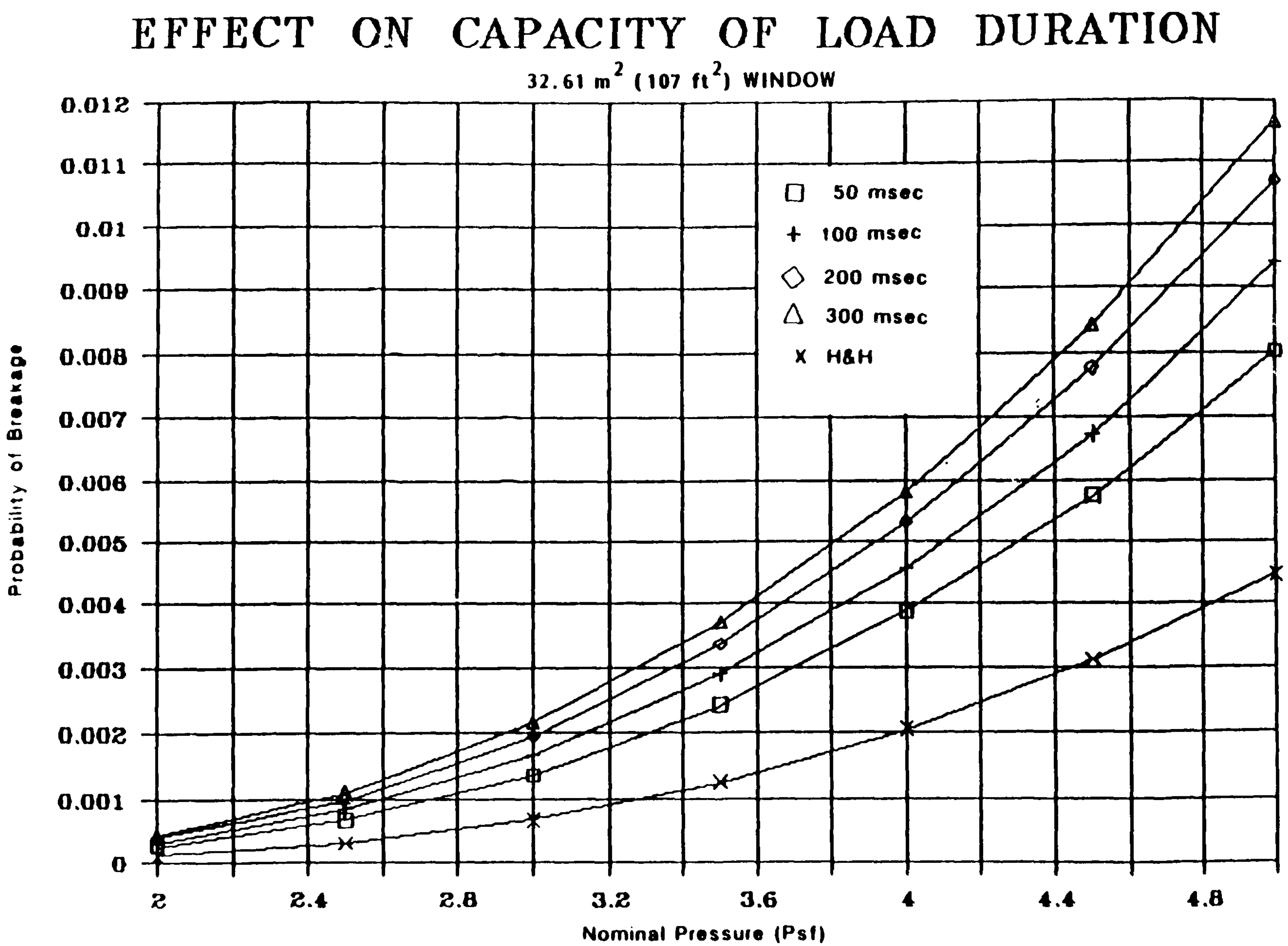

Figure 4-18. Sensitivity of the Capacity of a Window to Load Duration
($32.61\ m^2$ ($107\ ft^2$) Window, Nominal Overpressure 2-5 psf).

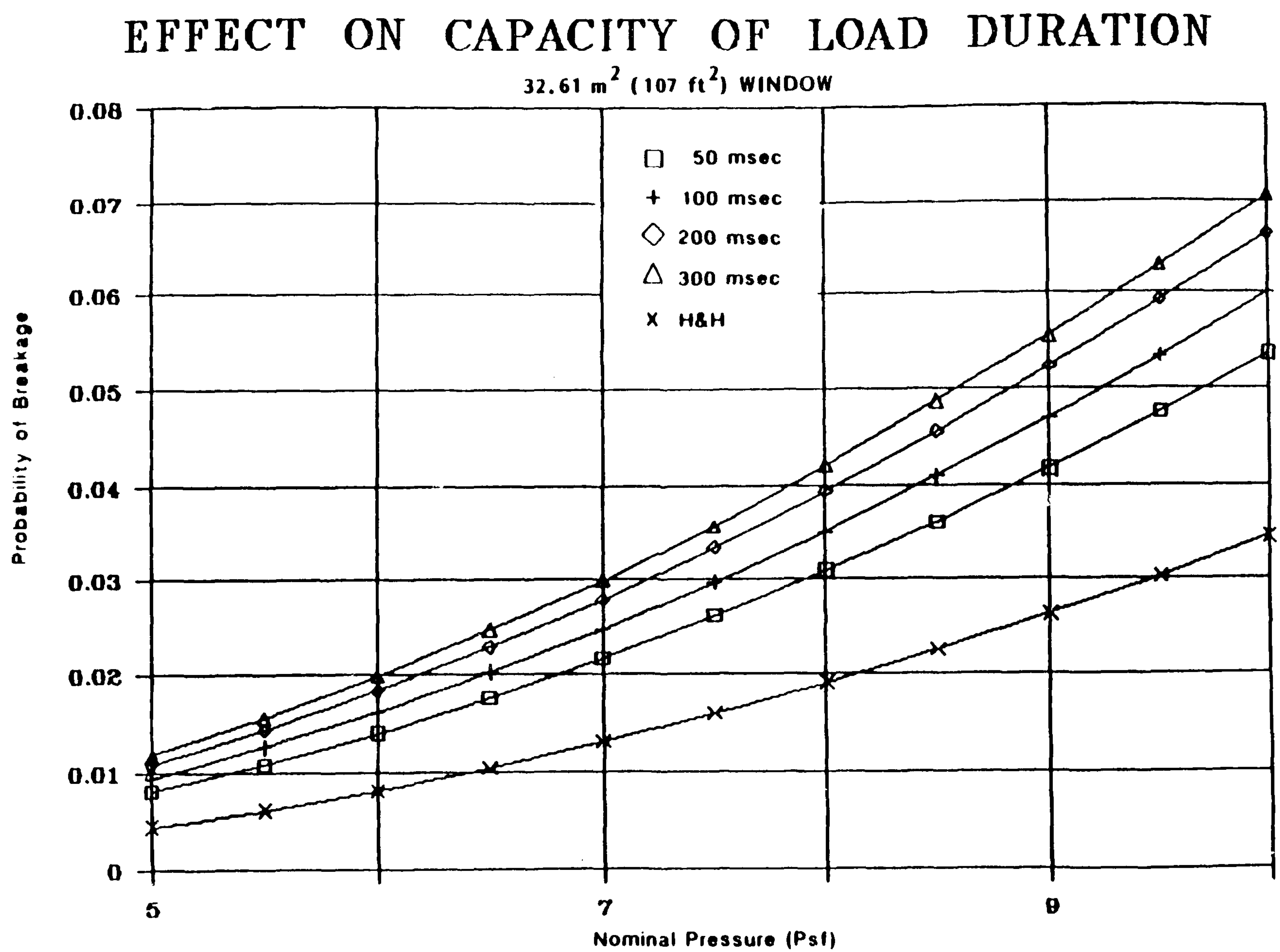

Figure 4-19. Sensitivity of the Capacity of a Window to Load Duration
($32.61\ m^2$ ($107\ ft^2$) Window, Nominal Overpressure 5-10 psf).

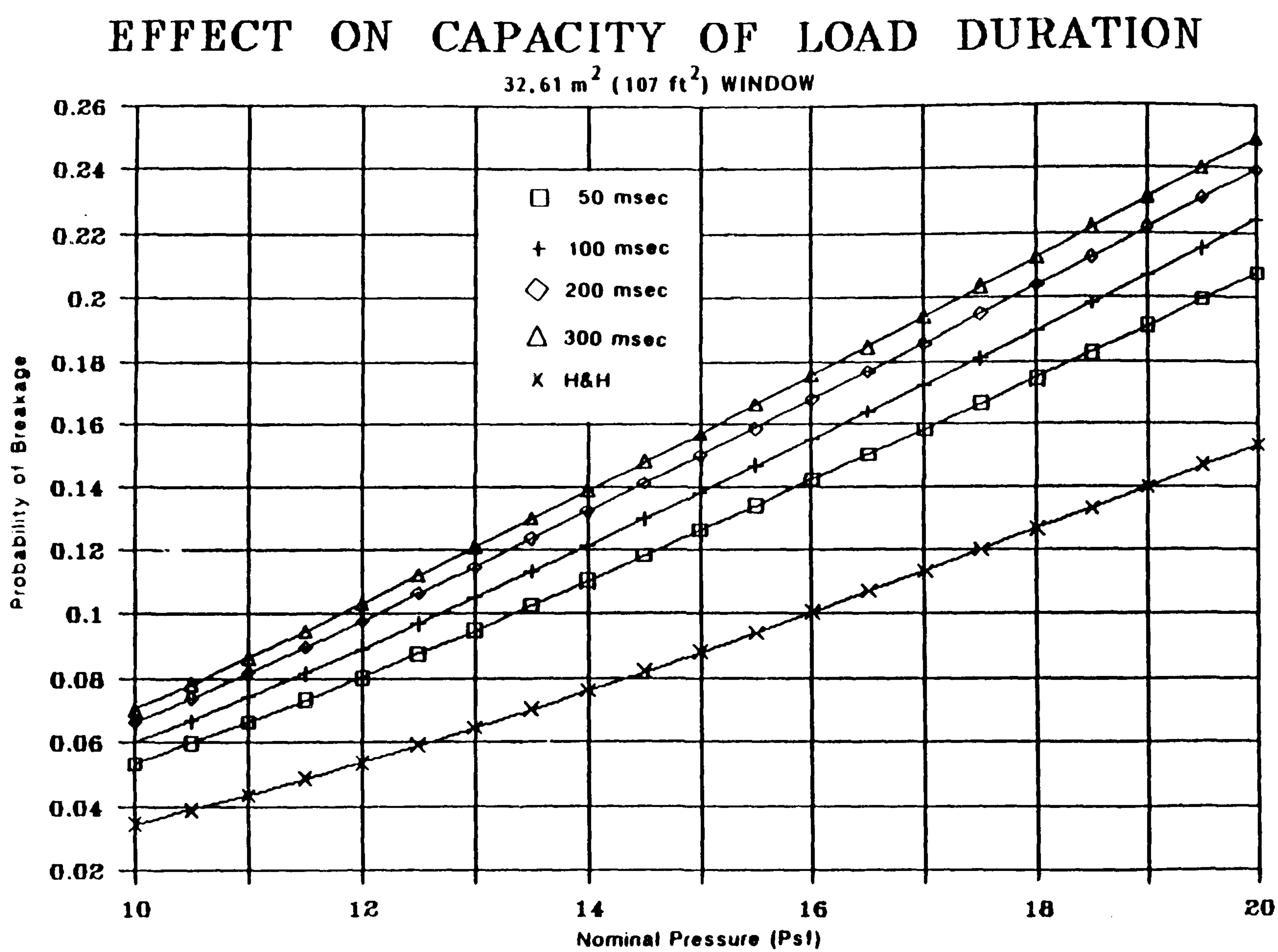

Figure 4-20. Sensitivity of the Capacity of a Window to Load Duration
(32.61 m^2 (107 ft^2) Window, Nominal Overpressure 10–20 psf).

estimates which are consistently too low. At most the under estimation is a factor of 3.

The Hershey and Higgins model assumes that the breaking pressure is lognormally distributed. This assumption is supported by the Libbey-Owens-Ford data upon which their model is based. However, this probability distribution is by no means universally accepted. It has been treated as a normal distribution (25) and has been pronounced of unknown form -- but definitely not normal or lognormal (26). Notwithstanding this lack of universal acceptance, the lognormal distribution is analytically convenient and appears to have some reasonable level of support in the professional community.

4.3 Plaster Damage

In the treatment of plaster elements, Hershey and Higgins considered both ceilings and walls. The ceilings were typical for residential wood frame construction with the lath and plaster supported by timber ceiling joists. The walls considered consisted of party walls and exterior walls of a wood frame house. For the party walls, the lath and plaster were supported by vertical steel studs spaced at 16 in. (40.64 cm). For a wood frame house, the walls consist of vertical timber studs which support both the exterior finish as well as the interior plaster finish. The typical construction for wood frame houses uses 2 ft x 4 ft (.61 m x 1.2 m) timber studs spaced at 16 in. (40.64 cm).

The treatment of the plaster elements is patterned after the treatment of glass elements. Arguing that walls and ceilings are comparable in size to a 107 ft^2 (32.6 m^2) window, Hershey and Higgins used the DAF statistics developed for that window for all of the plaster elements. However, it must be recognized that the DAF is most sensitive to the waveform and the natural

frequency of the element in question. Size alone is not indicative of the dynamic properties of the element. The 107 ft^2 (32.6 m^2) window has a natural frequency of 4 Hz. The ceilings and walls will typically have much higher natural frequencies. For example, Wiggins (6) states that walls of wood frame construction have measured natural frequencies of about 20 Hz. Consequently, the DAF statistics for the 107 ft^2 (32.6 m^2) window are not appropriate for plaster elements. The DAF for these elements should, instead, be based upon the theoretical development discussed later with the natural frequencies for the plaster elements calculated using the simply supported beam model.

To model the diaphragm response of the plaster ceilings and walls, Hershey and Higgins used a simply supported plate idealization analogous to the glass windows. However, as a consequence of the effect of the structural members which support the lath and plaster, the two-way action plate model is not appropriate for the ceilings and walls. Since the ceiling joists and the wall studs span in one direction, one way action is inferred. As a result, a simply supported beam model is a more appropriate way to represent the response behavior of the ceilings and walls rather than the plaster itself.

As an example, consider the plaster ceiling studied by Hershey and Higgins. The lath and plaster were supported by 15.5 ft (4.72 m) long, 2 ft x 8 ft (.61 m x 2.4 m) ceiling joists, spaced 2 ft (.61 m) apart. (Note that the spacing refers to the direction perpendicular to the span.) To develop the beam model for this system, one would consider the beam to have a span of 15.5 ft (4.72 m) with its cross section comprised of a single joist and a 2 ft (.61 m) width of the plaster. That is, the beam cross section would have the appearance of an inverted "T." The stress analysis for simply supported beams is straightforward, and the applied pressure from the sonic boom

can be easily translated into a corresponding maximum stress in the plaster.

Figures 4-21 through 4-23 show the effect of incorporating the beam response model. For the beam model two curves are shown representing the probability of plaster cracking for loading provided by a typical fighter and a typical bomber respectively. (The two types of aircraft are shown because of the difference in the load duration, and through it, the DAF.) These curves are compared with the results for the baseline model by Hershey and Higgins. The Hershey and Higgins model generates damage estimates which are too low for both cases. (In this example, the tensile strength of the plaster was taken to be 350 psi.)

The development of the beam model for the plaster walls follows the same logic outline for the ceiling model. The beam model would have a span equal to the height of the wall. Considering wood frame construction with the wall studs spaced 16 in. (40.64 cm) apart, the cross section of the beam model consists of a single stud with a 16 in. (40.64 cm) width of the interior plaster finish and a 16 in. (40.64 cm) width of the exterior finish. In this case, the beam cross section would then have the appearance of an "I."

Figures 4-24 through 4-26 show the effect of utilizing the beam model for walls for the same three cases that were presented for ceilings. Notice that for both walls and ceilings for both types of loads that the model proposed by Hershey and Higgins tends to <u>underestimate</u> the damage.

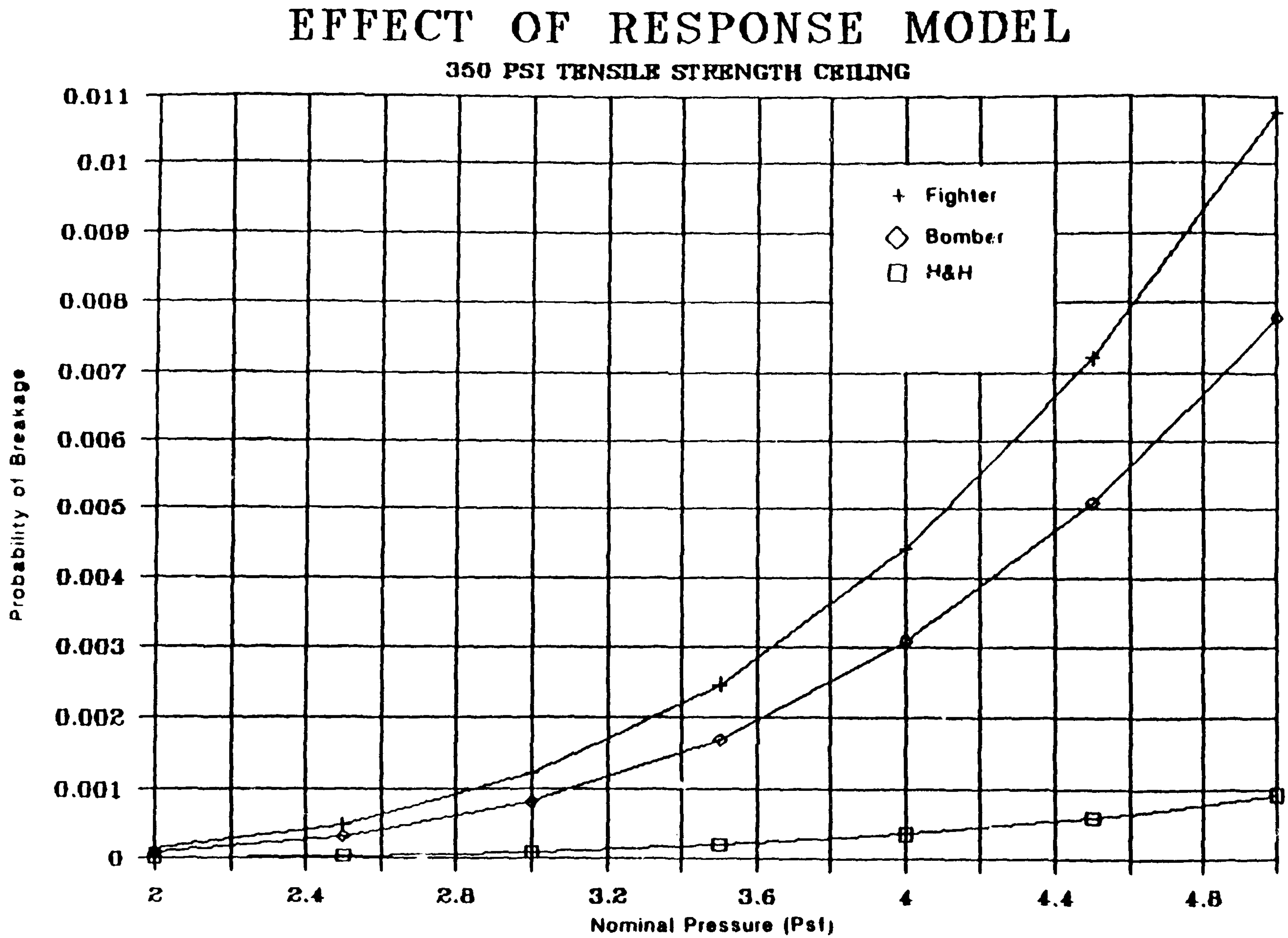

Figure 4-21. Sensitivity of the Probability of Ceiling Plaster Cracking to Response Model

(350 psi Tensile Strength Ceiling; Nominal Overpressure = 2-5 psf).

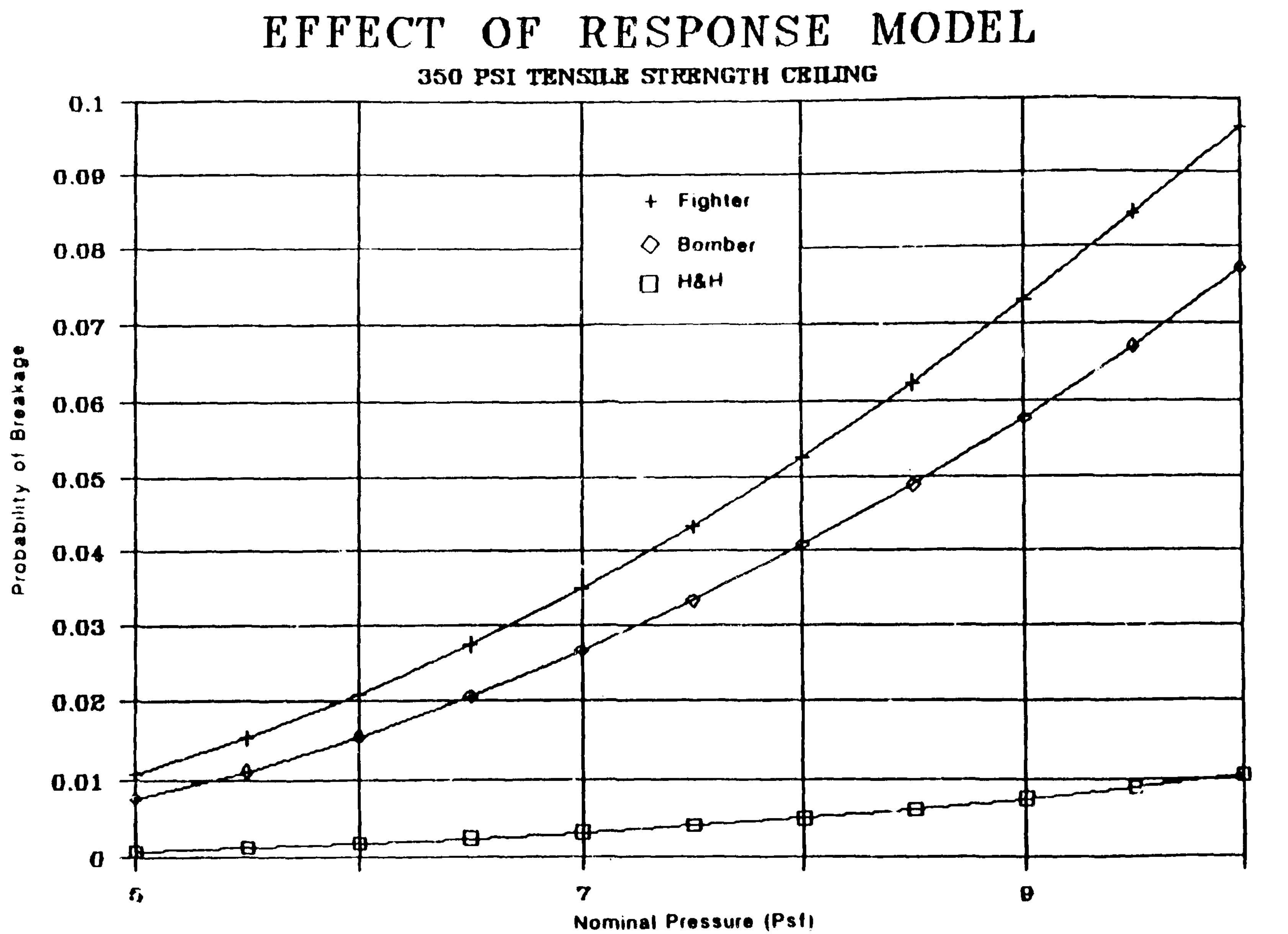

Figure 4-22. Sensitivity of the Probability of Ceiling Plaster Cracking to Response Model
(350 psi Tensile Strength Ceiling; Nominal Overpressure = 5-10 psf).

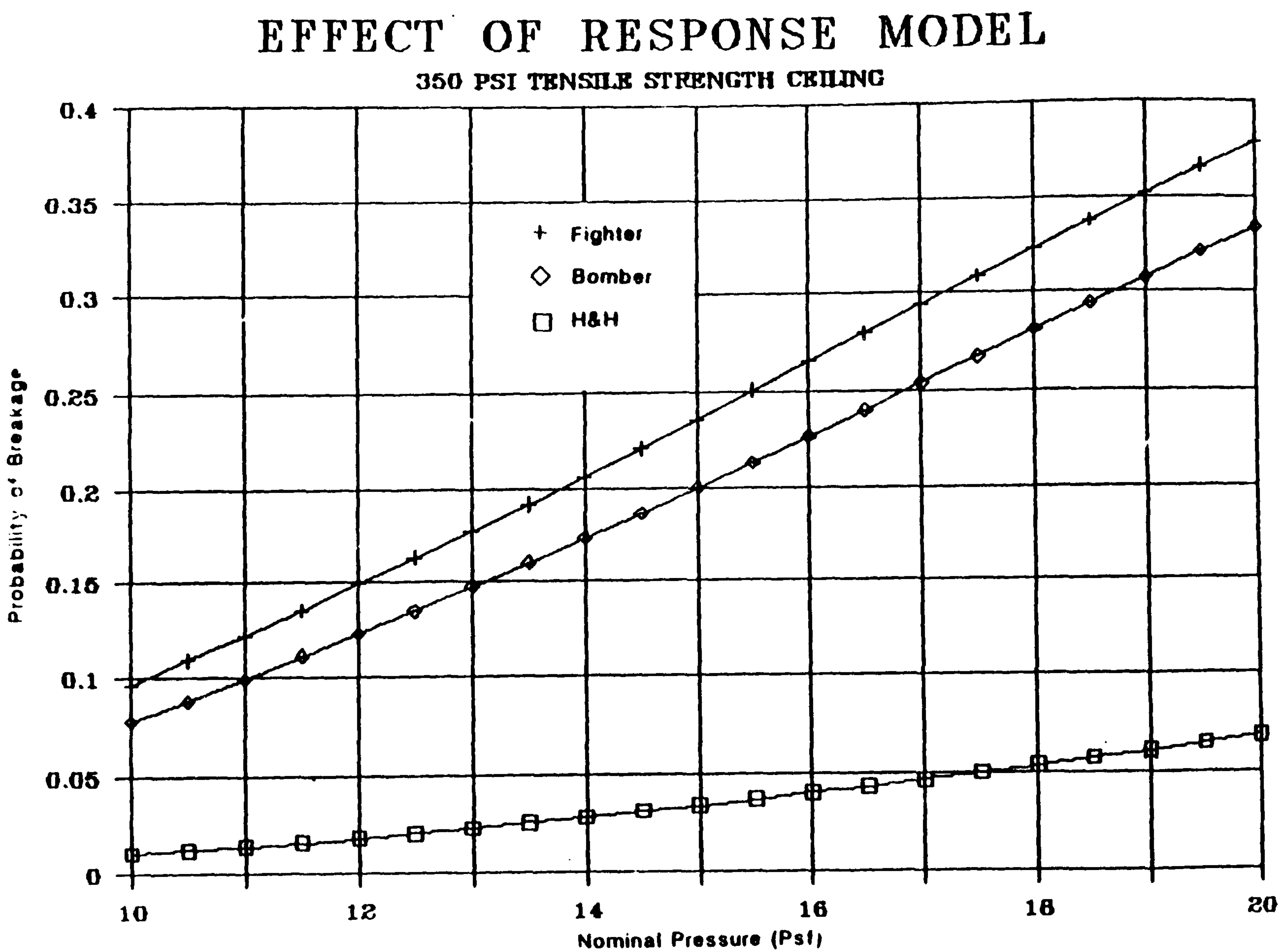

Figure 4-23. Sensitivity of the Probability of Ceiling Plaster Cracking to Response Model

(350 psi Tensile Strength Ceiling, Nominal Overpressure = 10–20 psf).

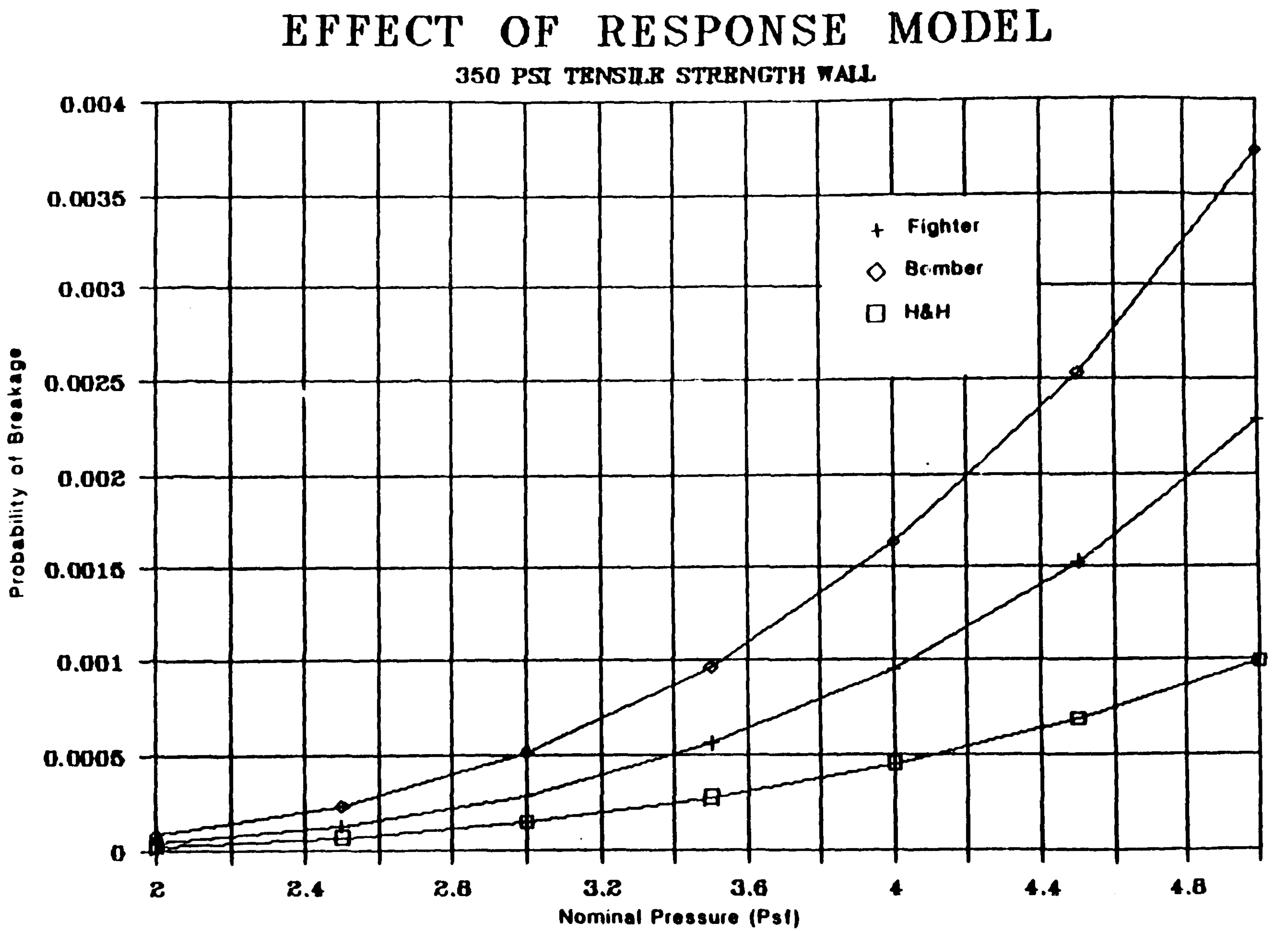

Figure 4-24. Sensitivity of the Probability of Wall Plaster Cracking to Response Model (350 psi Tensile Strength Wall, Nominal Overpressure = 2-5 psf).

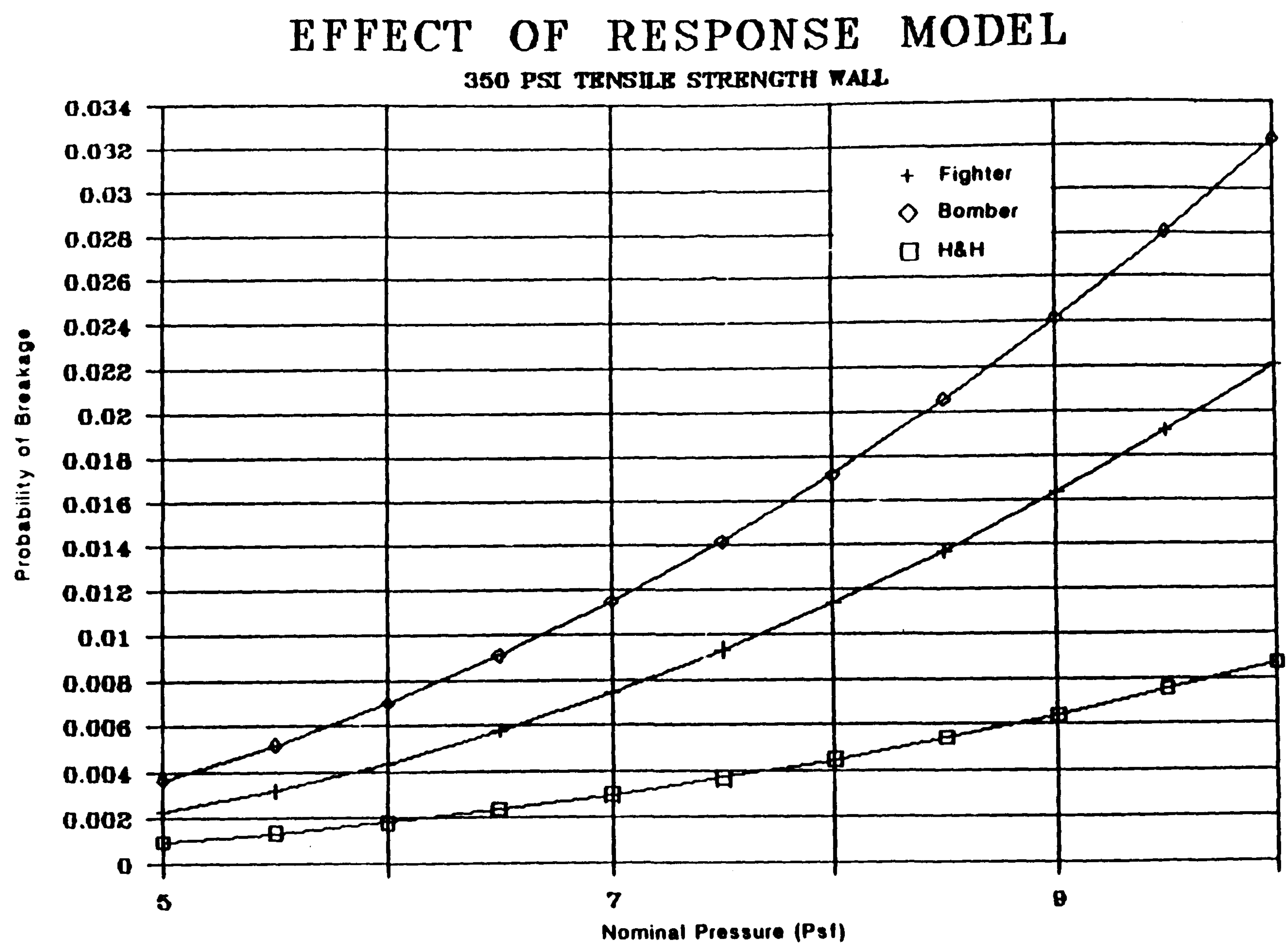

Figure 4-25. Sensitivity of the Probability of Wall Plaster Cracking to Response Model

(350 psi Tensile Strength Wall, Nominal Overpressure = 5-10 psf).

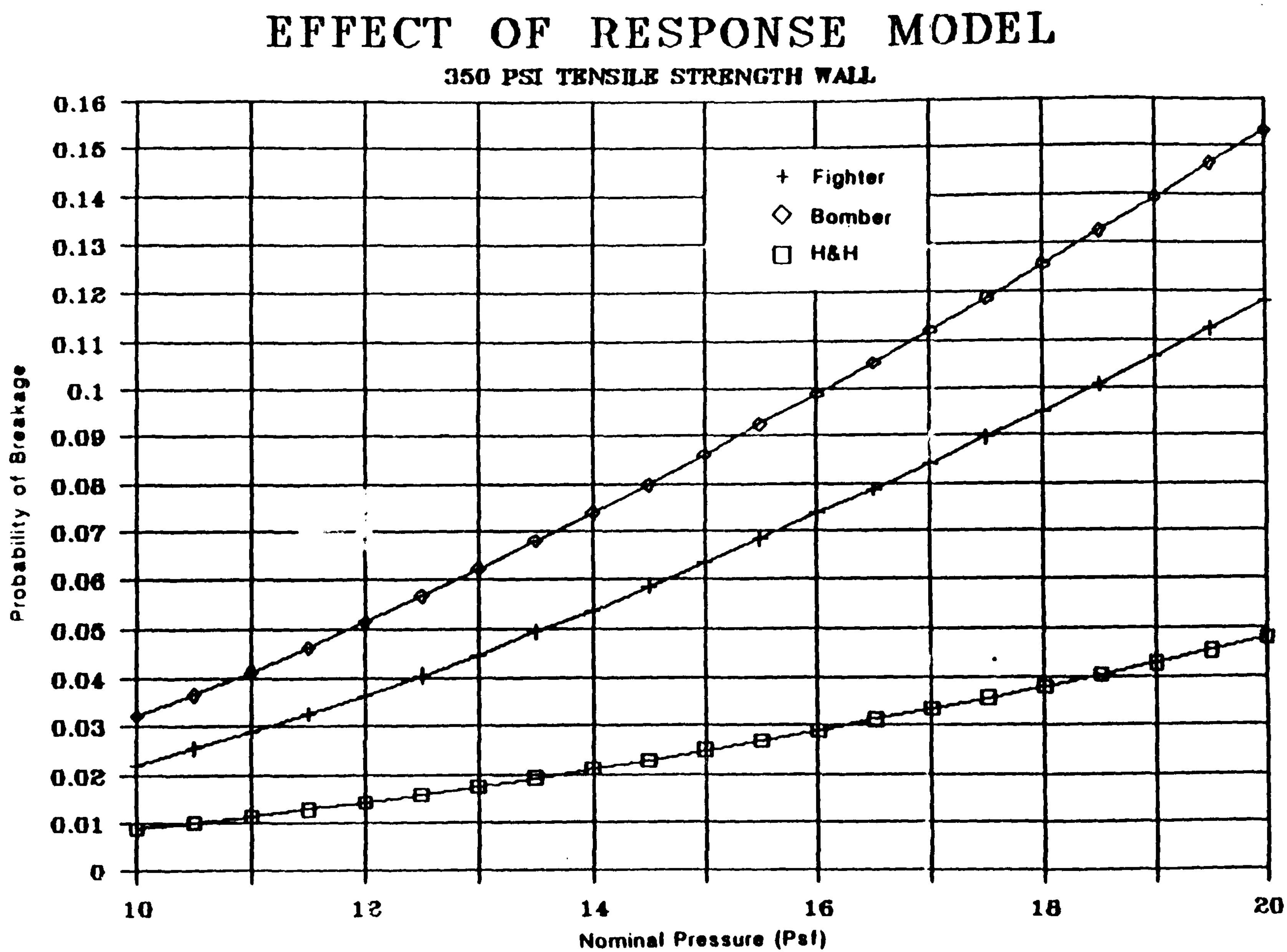

Figure 4-26. Sensitivity of the Probability of Wall Plaster Cracking to Response Model

(350 psi Tensile Strength Wall, Nominal Overpressure = 10-20 psf).

4.4 Bric-a-brac Damage

Even though the treatment of bric-a-brac in the model proposed by Hershey and Higgins is built based upon only two "data points" and is thus less than totally satisfying, there is little prospect of being able to make significant improvement on their results. The actual vulnerability of bric-a-brac is dependent upon the details of their placement as well as their stability and delicacy. Meaningful inventories of bric-a-brac as a function of region or type of facility are likely to be prohibitively expensive relative to the increased knowledge realized. Consequently, it is recommended that this model be accepted as is, with the understanding that the uncertainty in the damage estimates it produces is very large.

4.5 Brick Damage

Brick is a far stronger material than any of the other materials considered by Hershey and Higgins; brick mortar will experience shrinkage, and temperature and humidity changes will produce cracks in the mortar long before any sonic boom effects would be noticeable. Their fundamental conclusion that brick structures are not at risk from sonic booms is sound. While the results of their model for free-standing brick walls are plausible, insufficient details are provided as to parameter values to review these models critically or to provide NSBIT with a traceable, defensible methodology.

4.6 Alternative Probability Distribution

The lognormal probability distribution upon which all of the damage estimates are based assumes that the random variables can be as small as zero and arbitrarily large. To explore the consequences of the use of an unbounded distribution it is valuable to consider a set of probability distributions defined over fixed, finite intervals.

Looking ahead to Section 6 of this report, four structural element categories were selected for this evaluation. The categories chosen were selected because of the prevalence of these elements. The categories selected were Type B windows (panes with areas of 2 to 10 ft^2 (.61 to 3.05 m^2) and a thickness of 3/16th in. (.478 cm)), Type C windows (panes with areas of 10 to 50 ft^2 (3.05 to 15.25 m^2) and a thickness of 1/4 in. (.635 cm), Type A plaster (plaster ceilings) and Type B plaster (wood frame plaster wall).

The first step in this analysis was to estimate the limits of each random variable (P_G, DAF, and P_f/P_o). Table 4-1 indicates their limits. Using these values and the best estimate of P_e/P_f ($E(P_e/P_f) = 0.75$), it is possible to calculate a best estimate of a threshold pressure, P_{min}, for damage of each of these elements.

$$P_{min} = \frac{\mathrm{Min}(P_G)}{\mathrm{Max}\ (\mathrm{DAF})\ \mathrm{Max}(P_f/P_o)\ E(P_e/P_f)} \qquad (4\text{-}4)$$

Similarly, by assigning an upper bound to P_e/P_f ($\mathrm{Max}(P_e/P_f) = 4.0$), a minimum threshold pressure for materials in good condition can be calculated as

$$\mathrm{Min}(P_{min}) = \frac{\mathrm{Min}(P_G)}{\mathrm{Max}(\mathrm{DAF})\ \mathrm{Max}(P_f/P_o)\ \mathrm{Max}(P_e/P_f)} \qquad (4\text{-}5)$$

Table 4-1 Modeled Limits of Random Variables

ELEMENT	BREAKING PRESSURE		DAF		P_f/P_o	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Type B Window	220.0	450.0	1.62	1.95	0.40	1.65
Type C Window	68.0	145.0	1.00	2.15	0.40	1.65
Type A Plaster	13.0	25.0	0.80	2.20	0.40	1.65
Type B Plaster	39.0	53.0	1.24	1.88	0.40	1.65
Predamaged Type B Window	22.0	45.0	1.62	1.95	0.40	1.65
Predamaged Type C Window	6.8	14.5	1.00	2.15	0.40	1.65

Table 4-2 presents these damage threshold estimates. This analysis supports the intuitive result that good quality materials do not normally fail under common sonic boom load levels. Note, however, that extreme variations in the external load to freefield ratio, such as would be associated with an interior corner, does lead to much lower overpressure damage thresholds. These exceptional loading conditions can result in much lower damage thresholds than would be otherwise anticipated.

Table 4-2 "Threshold" Damage Pressures

MATERIAL	OVERPRESSURE DAMAGE THRESHOLDS (PSF)	
	BEST ESTIMATE	MINIMUM
Good Type B window	79.0	15.0
Good Type C window	26.0	4.9
Good Type A plaster	4.8	0.9
Good Type B plaster	14.0	2.6
Predamaged Type B window	7.9	1.5
Predamaged Type C window	2.6	0.49

As a final step in the damage threshold analysis this procedure has been extended to predamaged Type B and Type C windows. The results and parameters employed are shown in the last two lines of Tables 4-1 and 4-2 respectively. Notice that the combination of predamaged glass panes and extreme ratios does result in normal overpressure damage thresholds typical of many supersonic operations.

As a second step in investigating the consequences of choosing the lognormal distribution on damage probabilities, an alternative probability distribution was used, the beta distribution. The beta distribution is a versatile

distribution defined on a finite interval. To assure reasonable results, the simulation parameters were confined to those which produce unimodal distributions. The values shown in Table 4-1 for intervals over which the random variables are defined reflects this adjustment.

A Monte Carlo simulation study was made of the damage probability distribution for predamaged Type C windows employing 100,000 samples for each random variable. This analysis was interpreted for both best estimates and lower bound values of the P_e to P_f ratio.

Figures 4-27 and 4-28 present a comparison of the results of this simulation with the damage probabilities associated with the lognormal distribution. The first figure shows these results based upon the best estimate of the ratio P_e/P_f; the second figure is based upon the estimated maximum value of this ratio. In both instances the beta distribution results in a narrower distribution. The full effect of this result is not shown because of the limited sample size used in the simulation. However, it can be seen that there are several orders of magnitude difference in the damage probabilities calculated for the tails of the distribution. This difference is most pronounced for the portion of the distribution below a probability of 0.05 level on the lognormal distribution. Despite the dramatic differences at low overpressures there does not presently exist sufficient evidence to justify recommending a probability distribution other than the commonly accepted lognormal distribution.

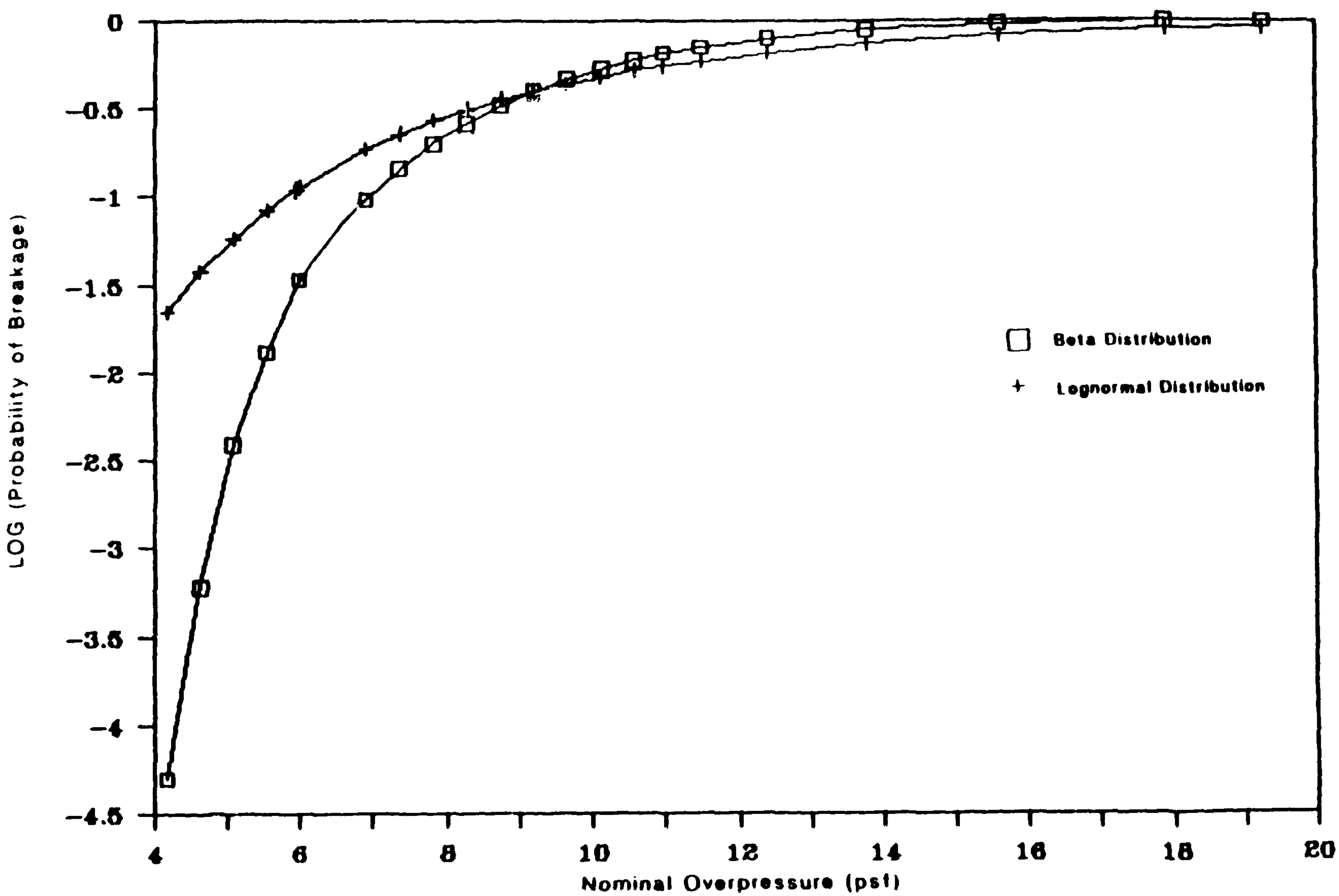

Figure 4-27. Comparison of Beta and Lognormal Probability Distributions for Type-C Predamaged Window Best Estimate of (P_e/P_i).

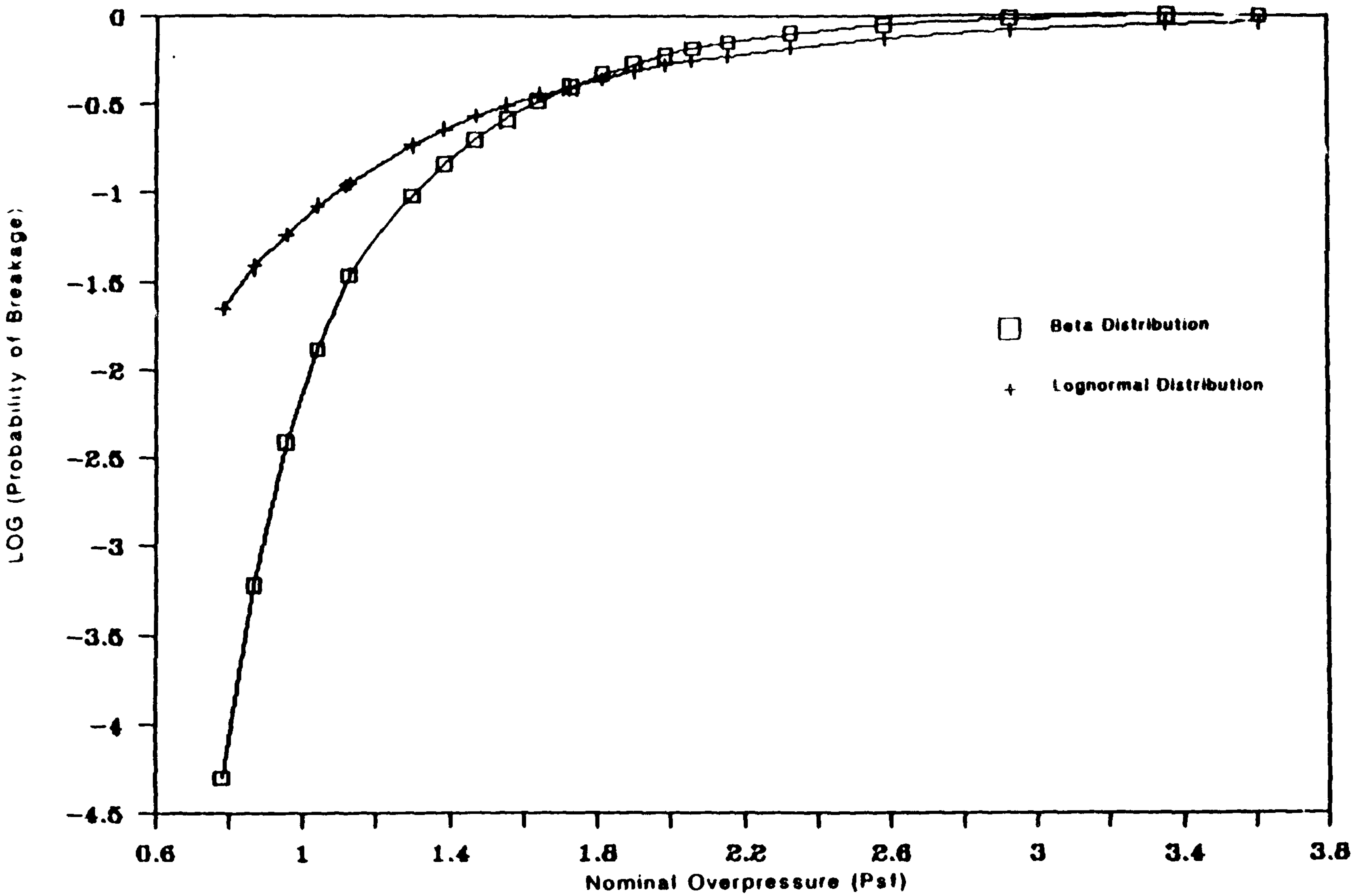

Figure 4-28. Comparison of Beta and Lognormal Probability Distributions for Type-C Predamaged Window (Low Estimate of P_e/P_f).

4.7 Summary of Model Enhancements

This section summarizes the enhancements and improvements to the Hershey and Higgins baseline model resulting from the critical review. The enhancements have been made to refine the statistics of the model parameters.

The model developed by Hershey and Higgins is probabilistic in form. It evaluates the probability that the load will exceed the capacity of a building element. Both capacity and load are modeled as dependent on parameters which have been assumed to be random variables. A number of these parameters should not be treated as random variables because they systematically alter the characterization of a scenario. (For example, changing aircraft types or flight path systematically changes the sonic boom footprint and the load on exposed elements.) Similarly, aggregating a range of conditions by forming categories (e.g., type A windows) systematically redefines the damage assessment problem. A significant improvement in the model results from properly identifying which parameters are random variables and which ones have systematic effects. Random variables are incorporated in the estimate of the probability of damage. Systematic sources of variation are used to characterized the uncertainty in the estimates of the probability of damage. In addition, they can be used to specify confidence levels or levels of conservatism for the estimated damage probabilities.

The specific enhancements to the model parameters are as follows:

1. The statistics associated with the free field overpressures have been improved. Hershey and Higgins used statistics to define the P_f/P_o term

that are not appropriate for the main sonic boom carpet. Those used by Hershey and Higgins are representative of the carpet fringes where there is substantial scatter in the data. Using these statistics for the main sonic boom carpet overestimates the random variability. This tends to result in overestimates of breakage probabilities at low overpressures. The statistics for P_f/P_o adopted for the ASAN model are based on data measured in the central portion of the sonic boom carpet. This results in a substantial reduction in the random variability of the sonic boom load.

2. The treatment of the variability of the external load term, P_e/P_f, has been revised. In the baseline model, Hershey and Higgins treated this term as a random variable. The factors that control its variability are, however, systematic rather than random. The major sources of variability in this term are associated with the orientation of the structure with respect to the wave direction, the structure geometry, and the configuration of the surrounding structures and terrain. Therefore, for the ASAN model, the variabilities associated with P_e/P_f are treated as uncertainty terms which contribute to the uncertainty of the damage probabilities.

3. The load model is enhanced by the inclusion of focused sonic booms, whereas in the baseline model, only N-waves were considered. The location at which a focused boom occurs and the shape of the waveform are strongly dependent on the aircraft maneuver and the meteorological conditions.

Therefore, observed focused boom overpressures may vary significantly with respect to the predicted overpressures. In the absence of a sufficient database, a conservative approach is adopted applying the free field overpressure statistics proposed by Hershey and Higgins to the P_f/P_o ratio for focused booms.

4. The treatment of the dynamic amplification factors has been substantially improved. In the baseline model, Hershey and Higgins used measured experimental data to develop the DAF statistics. However, the experimental data came from only seven windows. A sample that small cannot be expected to provide a reasonable description of the exposed population. For some of the windows, the external load acting on the pane was not measured and had to be estimated. The panes were also subjected to loading waveforms having a wide variation in duration. As a result, the DAFs used in the baseline model had substantial uncertainties and were not appropriate for predicting damage to the entire window population.

   To improve the DAF statistics, DAF spectra were analytically calculated for typical sonic boom wave signatures, including N-waves and, for the first time, focused sonic booms. This approach provided much more flexibility in using the DAFs. A nominal DAF value can be obtained for any structural element if the dynamic characteristics of the element are described in terms of its natural frequency and a damping value, and the sonic boom waveform is described by a duration. The variabilities associated with randomness and

systematic uncertainty were evaluated by performing sensitivity studies. Random variabilities in the DAF result from variations in the shape of the loading waveform and from variations in the damping of the affected element. The systematic uncertainties are associated with deviations of the wave duration and of the natural frequency of the affected element from nominal values.

5. Improved response models are used for the plaster elements, resulting in more appropriate statistics for the DAFs and the element capacities. For plaster ceilings and walls, flexure models are employed that better represent the behavior of these elements than the models used by Hershey and Higgins. In the baseline model, plaster elements were treated as plates. However, the DAF values used for the ceilings and walls were taken from values for a 107 ft^2 (32.6 m^2) window. It was argued that because a wall is approximately the same size as the large window, the window DAF values could be applied to the walls. Unfortunately, size alone is not a meaningful parameter to characterize the DAF. The DAF is strongly dependent on the natural frequency of the affected element. A plaster wall or ceiling has a much higher natural frequency than a 107 ft^2 (32.6 m^2) window. Using an appropriate analytical structural model to represent the flexure of the plaster ceilings and walls, appropriate natural frequencies were evaluated resulting in improved DAF statistics. Also by using an appropriate analytical model, improved capacity statistics were developed.

5. CUMULATIVE DAMAGE

5.1 Introduction

Cumulative sonic boom damage is defined to be the damage from repeated booms in excess of the net sum of the damage from each individual boom. This damage can be interpreted as a fatigue effect. Quantifying the cumulative damage requires relating the damage to the boom strength and the number of boom exposures.

This section documents a review of models for cumulative damage effects to conventional structures subjected to repeated sonic booms. The most significant information is summarized and the models potentially applicable to the recommended single event model are evaluated. Then an investigation of the cumulative damage effect is conducted. Using the candidate models identified in the literature review, modifications are made to the single event model to incorporate the fatigue effects. Damage probabilities for the repeated boom case are compared with the single event damage probabilities to assess the incremental contribution of the cumulative damage effect. This assessment provides a basis for making recommendations for a cumulative damage model.

5.2 Review of the Cumulative Damage Literature

The cumulative damage effect from repeated sonic booms has been investigated primarily through experimental studies. These studies have included the full-scale overflight tests as well as several laboratory test programs. In addition, damage surveys have attempted to compare the damage from repeated booms to the damage from naturally occurring environmental factors.

5.2.1 Field Tests and Damage Surveys

Overflight field tests sponsored by the FAA were conducted from 1964 to 1965 at Oklahoma City and at the White Sands Missile Range (13, 14). The objective of the Oklahoma City test program was to study public reaction to 1.5 to 2.0 psf sonic booms. Over 1,200 sonic boom overflights were performed. During the White Sands tests, 1,494 sonic booms were generated with overpressures up to 38 psf. In both programs, residential structures were targeted for study. Existing structures were monitored and, at White Sands, several test structures were constructed for the study.

The structures were carefully monitored during the test periods. The plaster elements in the structures were inspected to study the rate at which cracks developed. Crack measurements were made during both the overflight tests as well as during the "quiet" periods without sonic booms. In the White Sands tests, cracking tended to increase more rapidly during the boom periods than the nonboom periods for nominal overpressures of about 10 psf. In the Oklahoma City tests, there was no evidence of damage or a cumulative damage effect for overpressures up to 2.0 psf. From both of these test programs, a cumulative damage effect could not be positively identified. We found that natural environmental conditions produced substantial "noise" in the crack data making it difficult to distinguish the damage from the sonic booms. However, the data suggested that there may be a cumulative damage effect for overpressures greater than about 10 to 11 psf.

It must be recognized that by attempting to track the cumulative effects of repeated booms over an extended period, some of the damage observed in a structure will be due to naturally occurring forces. This damage can be attributed to temperature, humidity, wind loads, foundation settlement, or

human activity. Wiggins (15) revisited the White Sands site 7 years after the overflight tests had been completed to examine the structures and evaluate the natural deterioration that had occurred over that period. By comparing the observed damage with the damage recorded during the overflight tests and using information on the sonic boom activity during the interim 7 years, Wiggins found that natural deterioration had a far greater influence on the observed cumulative damage than the sonic booms. From this damage survey, the cumulative damage effect was difficult to identify as a function of boom strength and number.

Similarly, Webb (16) has conducted damage surveys in Europe to compare the relative influences of sonic booms and natural forces. Damage claims data from Western England arising from the Concorde flight test program were used to describe the damage rates due to sonic booms. To evaluate the damage rates from environmental factors, Webb conducted a questionnaire survey of the residents of an area which was not subjected to the sonic booms, yet was near enough to the Concorde test area that the climate and other environmental factors were similar. Neither the residents nor the questioners were informed that the survey was associated with sonic boom damage. By comparing the damage rates, Webb concluded that the sonic boom damage was small in comparison to the damage from normal environmental factors.

Recognizing that the damage claims from the Concorde test program came from only 18 flights, Webb also conducted similar surveys in the Federal Republic of Germany. An area was selected which was exposed to an average of 400 sonic booms per year from North Atlantic Treaty Organization (NATO) aircraft. A nearby area unaffected by sonic booms was carefully selected to assure statistical similarity. Webb found from the damage

surveys that there was not a significant increase in the building damage rates due to the frequent sonic booms.

It must be noted that the use of damage claims data relies heavily on the validity of those claims. The number of claims must be truly representative of the amount of damage; i.e., there cannot be excessive under-reporting or over-reporting of damage. In addition, the quality of the survey information depends on the ability of the observer to detect the damage.

The relative magnitude of the damaging effects of naturally occurring forces has also been reported in field tests on the effects of ground vibrations from underground blasting. Stagg et al. (17) found that human activity - or temperature and humidity variations - produced strains in the plaster walls of a wood frame house which were equivalent to those corresponding to a peak ground velocity of 1.2 in. (3.048 cm)/second. In comparison, it was found in that study that the minimum damage threshold for the underground blasting corresponded to a peak ground velocity of 1.0 in. (2.54 cm)/second. That is, the effects of natural phenomena were in excess of the minimum damage threshold. To relate the ground motion to sonic boom overpressures, Wiggins (18) has estimated that a peak ground velocity of 1.0 in. (2.54 cm)/second corresponds to an overpressure of about 3 psf. From this data it can be interpreted that at low overpressures (approximately 3 psf or less), the effects of environmental factors are more severe than those from the sonic booms. Another observation is that these blast test results are consistent with conclusions drawn by Wiggins regarding the existence of damage thresholds. Further, the estimated overpressure level is consistent with the results observed at Oklahoma City where no damage was observed for overpressures less than or equal to 2 psf.

It is clear from these field tests and damage surveys that at low overpressures, sonic boom cumulative damage is very difficult to separate from damage due to environmental factors. Test data indicate that the environmental factors are more severe than the sonic boom effects at low overpressures. It is also suggested that there is a damage threshold overpressure below which damage would not be expected.

5.2.2 Laboratory Tests

Given that the cumulative damage from repeated sonic booms was difficult to identify in the field tests due to the "noise" from the environmental effects, the next step in understanding the sonic boom fatigue behavior of glass and plaster involved laboratory testing. An advantage of working under controlled laboratory conditions was that the environmental factors could be minimized and the effects of the repeated booms alone could be studied.

To describe the cumulative damage effect, researchers have attempted to establish fatigue relationships for glass and plaster relating the material capacity to the number of sonic boom load cycles, similar to S/N curves for metals. This type of approach appears to be a promising form for application with the recommended single event model in that the material capacity can be related to the number of boom exposures.

Kao (19) conducted repetitive sonic boom tests on eight 48 x 48 x 3/32 in. (121.92 x 121.92 x .239 cm) glass panes. The glass panes were subjected to simulated N waves with peak overpressures ranging between 4 and 24 psf with durations typically of 0.40 sec. Of the eight test specimens, six failed. Reviewing the test results indicated that the number of sonic boom loadings had virtually no influence on the breaking strength of the glass panes. The glass pane which was subjected

to the 24 psf booms withstood 87 loadings before failing. One test glass pane which was subjected to peak overpressures of 20 psf withstood 490 booms, while another glass pane broke after just two booms of 19.5 psf. One glass pane did not fail after 10,000 booms with a peak overpressure of 16 psf, but another glass pane failed after only 37 booms of 13 psf. The range of overpressures for the failed glass panes was 13 to 24 psf. This range is consistent with the expected variability in the breaking strength of glass panes. However, by comparing the number of boom exposures for glass panes with similar failure pressures, there is not a consistent trend as the number of boom exposures varies widely. Because there were so few test specimens, these results cannot be considered conclusive.

White (20) later conducted a similar repetitive sonic boom test program with 48 x 48 x 3/32 in. (121.92 x 121.92 x .239 cm) glass panes. The glass panes were not mounted in fixtures representative of typical installed conditions. Instead, the glass panes were held in the sonic boom simulator by special mountings which provided clamped boundary conditions. Fifty-eight glass panes were subjected to simulated N waves having overpressures ranging from 3 to 53 psf. Of the fifty-eight glass panes, four failed upon the first applied boom. Among those four, the applied overpressure ranged between 7 and 39 psf. Twenty-two glass panes withstood the repeated booms without failure and of those samples most withstood more than 10,000 load cycles.

Using the data for the glass panes that failed, White performed a regression analysis to arrive at a relationship between the sonic boom overpressure required for failure and the number of load applications. Noting that the number of applied booms covered several orders of magnitude, White's regression

curve related overpressure at which failure is expected to the logarithm of the number of boom exposures as

$$P = 30.8 - 1.615 \log N \quad \text{psf} \tag{5-1}$$

in which P is the peak overpressure of the sonic boom applied to the glass pane and N is the number of boom exposures. An interpretation of Equation 5-1 is that the glass pane could be expected to fail after N exposures to sonic booms with identical peak overpressures of P. Also, since P represents the peak overpressure applied to the glass pane, it can also be interpreted as the sonic boom breaking pressure. From Equation 5-1, the mean overpressure required for breakage under a single sonic boom is 30.8 psf. Note that the capacity decreases very slowly with increasing numbers of applied sonic booms.

A limitation of the fatigue relation shown in Equation 5-1 is that it relates the number of boom exposures to a single overpressure level for failure. The fatigue relation does not allow for the possibility of having a load history with varying amplitudes of the applied overpresure. For example, Equation 5-1 predicts a capacity of 10,000 boom exposures at identical overpressure levels of 24.3 psf. The same reduction in capacity would not be expected if the 10,000 boom load history contained 5,000 booms at some lower overpressure level, say 10 psf. It is uncertain whether or not the data and the fatigue relationship could be extrapolated to treat a sonic boom load history with repeated boom exposures having various overpressure levels.

A review of the data shows that there is great scatter and, as a result, a great deal of uncertainty in the regression curve. White found that the correlation between the data and the regression curve was very low. Another conclusion was that the scatter in the data tended to mask the cumulative damage effect. With these conclusions in mind, there does not appear

to be strong evidence for a cumulative damage effect in glass. However, there is a very limited amount of test data.

One limitation of these laboratory tests is that the mounting conditions used to hold the glass panes were not typical of the mounting systems expected in structures. Unlike a typical window glazing, the test conditions provided very secure clamped boundary conditions and were free from stress raisers. The lack of stress raisers itself would improve the capacity of the glass panes. In addition, it was initially intended to use a conventional wood molding held together with nails to mount the panes. Nevertheless, when this system was used, the nails and the molding became loose after only a few sonic booms. As a result, the mounting was replaced and the wood molding was not used throughout the test program. Unfortunately, the window supports are usually related to the likelihood of glass damage, either from stress raisers or from rattling in the support. Continuing the testing with the loose support would be expected to lead to failures much sooner than observed.

Pallant (21) reported on tests on leaded glass windows conducted in England. Tests were conducted to investigate the effect of repeated booms and to estimate damage threshold overpressures. In the repeated boom tests, the windows were subjected to a minimum of 450 simulated N waves with a peak overpressure of about 3 psf. No damage was observed under these conditions. In the damage threshold tests, the windows withstood overpressures of up to about 50 psf before slight damage was observed. This damage was the appearance of dust from the glazing putty used as a filler between the lead and the glass panes. Buckling of the lead framing and glass cracking was observed at overpressures of about 100 psf. These tests indicate that damage to leaded glass windows is unlikely under low overpressure sonic booms. The resiliency of the leaded

window is the result of the "softness" of the lead. Due to the flexibility of the lead, the windows were capable of withstanding large distortions. Another key finding from these tests is that temperature changes can cause considerable deflections in the window due to the thermal expansion of the lead. However, Pallant also found that these environmental effects may act to relieve the effects of repeated booms.

As with glass panes, there have been few laboratory tests dealing with the repetitive effects of sonic booms on plaster. Leigh (22) has conducted tests on 16 x 16 x 3/8 in. (40.64 x 40.64 x .95 cm) plaster panels. The test specimens were constructed of plaster alone with no lath or other supporting members. Leigh first conducted fatigue tests by loading the plaster panels with an acoustic shaker. A fatigue relationship was evaluated from seventeen data points by regression analysis. There was considerable scatter in the data and most of the points fell into the range of about 10 to 50 million load cycles. The fatigue relation developed by Leigh related the maximum plaster tensile strain to the logarithm of the number of load cycles as

$$\epsilon = 345 - 21.9 \log N \quad \mu \text{ inch/inch} \qquad (5\text{-}2)$$

where ϵ is the maximum tensile strain capacity of the plaster and N is the number of load cycles. An interpretation of Equation 5-2 is that the plaster could withstand N load cycles with a constant strain amplitude of ϵ before failing. The maximum tensile strain capacity under a single loading is then 345 μ inch/inch. Again, note that the capacity drops off very slowly with increasing numbers of boom exposures.

As with Equation 5-1, the fatigue relation does not allow for a load history with varying response amplitudes. The fatigue relation relates the number of load cycles to only a

single constant response amplitude. It is not clear whether the data could be extrapolated to treat a repeated boom load history which induced varying strain levels in the plaster.

By using strain in Equation 5-2, the fatigue relation is expressed in terms of a response quantity. This response quantity is in contrast to the glass fatigue relation in Equation 5-1 which was expressed in terms of the applied loading. However, for use with the recommended ASAN single event model, it would be preferable to be able to express the fatigue effect in terms of load capacity. This expression can be accomplished by taking advantage of the linear load/response behavior of the plaster elements. For a given number of load cycles, the strain capacity reduction from Equation 5-2 will be proportional to the reduction in the applied load capacity.

Leigh tested thirteen plaster panels under simulated N waves. The simulated sonic booms had peak overpressures of 10 psf and a duration of 0.10 sec. The panels were subjected to 1,000 booms and were inspected after every 100 booms. In addition, Leigh simulated preexisting wear in the panels by preloading them with an acoustic shaker for 10 million load cycles at a strain which was 40% higher than the strain produced by the N waves. Of the thirteen panels, only one failed. However, Leigh concluded that this failure was most likely due to an excessive clamping force used to hold the specimen. Leigh concluded that damage to plaster walls and ceilings would be unlikely in buildings in good repair when subjected to repeated sonic booms.

An obvious limitation of these data is that the plaster panels were not completely representative of plaster elements as they would appear in buildings, since they did not have lath or the structural support members. It seems plausible that the

repeated booms could weaken the bond between the lath and plaster.

Another experimental study on plaster wall panels was conducted by Peschke et al. (23). The test specimens were of 8 x 12 ft (2.44 x 3.66 m) standard wood frame construction wall panels consisting of 2 x 4 in. (5.08 x 10.18 cm) wood studs spaced at 16 in. (40.64 cm) on center, wood siding on the exterior, and on the interior, 3/8 in. (.95 cm) plaster board with a 3/8 in. (.95 cm) thick plaster finish. The specimens were subjected to 500 simulated sonic booms each at nominal overpressures of 1.0, 1.8, and 2.6 psf. With such low overpressures, the cracks in the plaster generally were not visible to the naked eye. To detect the cracks, ultraviolet light was used.

Although there was not a cumulative damage model proposed in this study, an important finding was the manner in which plaster cracks can develop. Slight nail popping was detected and it was found that the plaster cracks began in the vicinity of the nails used to attach the plasterboard to the studs. Even though special techniques were used to detect the cracks, the discovery does indicate that, as with windows, plaster damage from sonic booms may be initiated by stress raisers.

5.3 Evaluation of the Significance of Cumulative Damage

In this section, the impact of repeated sonic boom exposures on damage probabilities is investigated by comparing the damage predictions after numerous repeated booms with the single event predictions. The damage probabilities are evaluated using the recommended ASAN model as presented in Section 6. The ASAN single event model is modified to incorporate the sonic boom fatigue effects for glass and plaster which were discussed in the preceding section. The relative significance of the

cumulative damage effect is examined by comparing the damage probabilities after the repeated boom exposures with the damage probabilities produced by the ASAN single event model using the mean statistics and the mean plus one standard deviation statistics. The cumulative damage effect is also qualitatively compared with the effects from environmental factors. Although a definitive statement regarding cumulative damage cannot be made, an argument is made that the effect is small relative to the uncertainty in the ability to predict damage from a single exposure and to the damage generated by aging and environmental effects.

5.3.1 Comparison with the Single Event

The experimental fatigue relations for glass and plaster presented by White and Leigh, respectively, relate the material capacity to the number of boom exposures. For increasing numbers of sonic booms, the material strength decreases. In spite of the drawbacks discussed in the preceding chapter, they are used to provide an indication of the potential cumulative damage. These were the only models to offer some relationship between the material capacity and the number of exposures. The cumulative damage effect is simulated in the single event model by using reduced element capacities estimated from the fatigue relations. No other modifications are made to the damage model.

It is assumed that the materials are initially healthy and in good repair. There are no provisions for evaluating the incremental damage that may occur with each successive sonic boom. Only the effects of the sonic booms are included as there is no adjustment for the natural deterioration due to aging in the material.

A conservative estimate of the expected number of sonic booms a structure might be exposed to in an MOA is about 200/ year (24). Assuming that the lifetime of a building is 50 years, this translates to 10,000 boom exposures over the life of the building. While it is expected that window replacement and replastering of walls and ceilings would be expected to occur during a 50-year design lifetime of a building, assuming the same elements are present for the 50-year period will result in a conservative estimate of the cumulative sonic boom damage effects. The cumulative damage effect is investigated by adjusting downward the element capacities to reflect the losses in strength after the boom exposures.

5.3.1.1 Windows

White tested 48 x 48 x 3/32 in. (121.92 x 121.92 x .238 cm) glass panes. According to the size category definitions presented in Reference 1, those glass panes would be classified as Type C windows. The category definitions presented in Reference 1 are shown in Table 5-1. To utilize White's data in the recommended single event model, we have replaced the mean capacity values for the category C windows with White's experimental values, since the data were given as breaking pressures. That is, the mean breaking pressure for the new glass pane is 30.8 psf for a single exposure.

Recall that White's fatigue relation was expressed in terms of the applied overpressure and the number of boom exposures at that overpressure for failure. Here the fatigue relationship will be used to estimate the reduction in capacity for the glass pane after repeated exposures. Table 5-2 shows the variation of the mean breaking pressure with the number of booms as predicted using the fatigue relation presented by White. Values are given for 1, 1,000, 2,000, 5,000, and 10,000 booms. At a rate of 200 booms per year, the multiple booms correspond to exposure

periods of 5, 10, 25, and 50 years. For the repeated boom cases in Table 5-2, we assumed that the load history of the glass pane is defined by the number of exposures and the corresponding applied overpressure shown. For example, for the 10,000 boom case, we assumed that the glass pane has survived 9,999 boom exposures at 24.3 psf and that the breaking pressure for the next boom is 24.3 psf. Equation 5-1 did not allow for a load history with boom exposures at varying overpressure levels. However, it is thought to be conservative to consider a load history at these constant, high overpressures. At 10,000 booms, the predicted capacity is 79% of the initial strength. However, there is not a substantial change between 1,000 booms and 10,000 booms. Recall from Equation 5-1 that the predicted breaking pressure decreased only 1.6 psf with each order of magnitude increase in the number of booms.

Table 5-1 Categories of Windows

Category	Area Range ft^2 (m^2)	Thickness in. (cm)	Natural Frequency (Hz)	Representative Frequency (Hz)
A	0.00 - 2.00 (0.00 - 0.61)	3/32 (.238)	80 - 175	95
B	2.00+ - 10.00 (0.61+ - 3.05)	3/16 (.476)	30 - 140	60
C	10.00+ - 50.00 (3.05+ - 15.24)	1/4 (.635)	8 - 45	18
D	50.00+ - 100.00 (15.24+ - 30.50)	5/16 (.794)	5 - 14	6
E	>100.00 (>30.50)	5/16 (.794)	2 - 7	4

Table 5-2 Predicted Mean Breaking Pressures for the Example Window for Repeated Sonic Booms

No. of Sonic Booms	P_G (psf)	log (P_G)
1	30.8	1.475
1,000	26.0	1.402
2,000	25.5	1.393
5,000	24.8	1.381
10,000	24.3	1.372

The parameter values used in the single boom exposure damage model are shown in Tables 5-3a and 5-3b for N waves and focused waves, respectively. Since White (20) tested glass panes of only one specific size in developing the fatigue relation, there is no uncertainty term associated with the variation in the breaking pressure among the members of the window category. The mean and variance of the log(DAF) term are the values presented for the category C windows in Reference 1. In Table 5-1, the representative frequency for the category C windows is 18 Hz. White (20) reported measured natural frequencies for the tested glass panes as 14 Hz. Recognizing that the DAF values are sensitive to the natural frequency of the element, for the purposes of illustration here, the DAF values for the category C windows are thought to be sufficiently accurate. The uncertainty term for the logarithm of the DAF includes only the uncertainty associated with the loading pressure wave duration interval which was selected for the single event model.

Table 5-3a <u>Statistics for the Window Example for N-waves</u>

	Mean	Variance	Uncertainty
log (P_G)	1.475	2.63×10^{-2}	--
log (P_e/P_f)	-0.1251	--	4.39×10^{-2}
log (P_f/P_o)	-0.0753	4.0×10^{-3}	--
log (DAF)	0.2185	8.37×10^{-3}	1.20×10^{-4}

Table 5-3b <u>Statistics for the Window Example for Focused Waves</u>

	Mean	Variance	Uncertainty
log (P_G)	1.475	2.63×10^{-2}	--
log (P_e/P_f)	-0.1251	--	4.39×10^{-2}
log (P_f/P_o)	0.0471	4.46×10^{-2}	--
log (DAF)	0.0582	1.11×10^{-2}	8.0×10^{-4}

In Figure 5-1a, the breakage probabilities for N waves are compared for the single event case (the mean and mean plus one standard deviation statistics) and for the modified condition at 10,000 booms. The figure shows that the damage probabilities for the window after 10,000 boom exposures fall between the single event damage probabilities for the mean and mean plus one standard deviation statistics. That is, the damage prediction using White's fatigue relationship falls within the uncertainty of the single event model.

For overpressures greater than 10 psf, the differences in the damage probabilities are easy to observe. However, at the low overpressures, the scale of the graph makes it difficult to see the differences in the curves. Figure 5-1b shows an expanded view of the low overpressure range in which the logarithm of the probabilities is plotted versus the nominal overpressure. Again, it is observed that the cumulative damage prediction using White's fatigue relation falls within the uncertainty of the single event damage prediction. Figures 5-2a and 5-2b show the breakage probabilities for focused waves. The observed results are similar to those from the N wave case.

Given the results shown in Figures 5-1 and 5-2 along with the conclusions by White, the cumulative damage effect cannot be conclusively shown. By reducing the strength of the glass pane to account for the repeated booms, the increase in the probabilities of breakage was not large enough to outweigh the uncertainty in the single event damage prediction.

Since White based the fatigue relation on the test data for only 48 $in.^2$ (121.92 cm^2) glass panes, it is not clear how the repeated booms would affect glass panes of different sizes. The fatigue relation cannot be extrapolated to apply to glass panes having sizes other that that tested. In addition, a load history with boom exposures at varying overpressures cannot be treated directly. We emphasize that the fatigue relation addressed only the effects of the repeated loading on the material itself. The fatigue relation did not include the influences of abrasion, rattling, or stress raisers in the window mounting. These limitations do not allow for a comprehensive model to be recommended to represent the cumulative damage effect for glass panes.

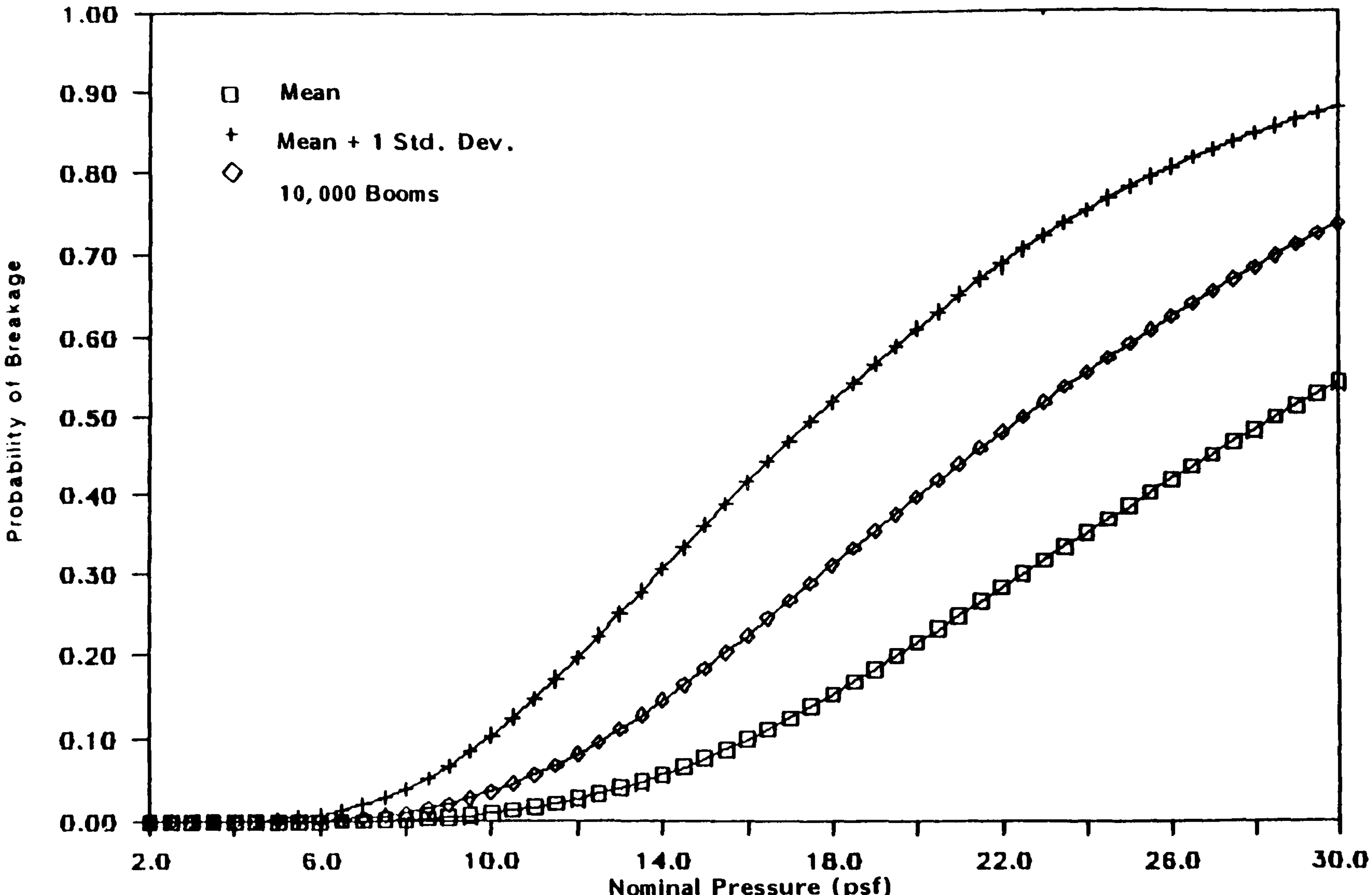

Figure 5-1a. Example Window Breakage Probabilities for Single and Repeated N-Wave Sonic Booms (Over Pressure Range = 2-30 psf).

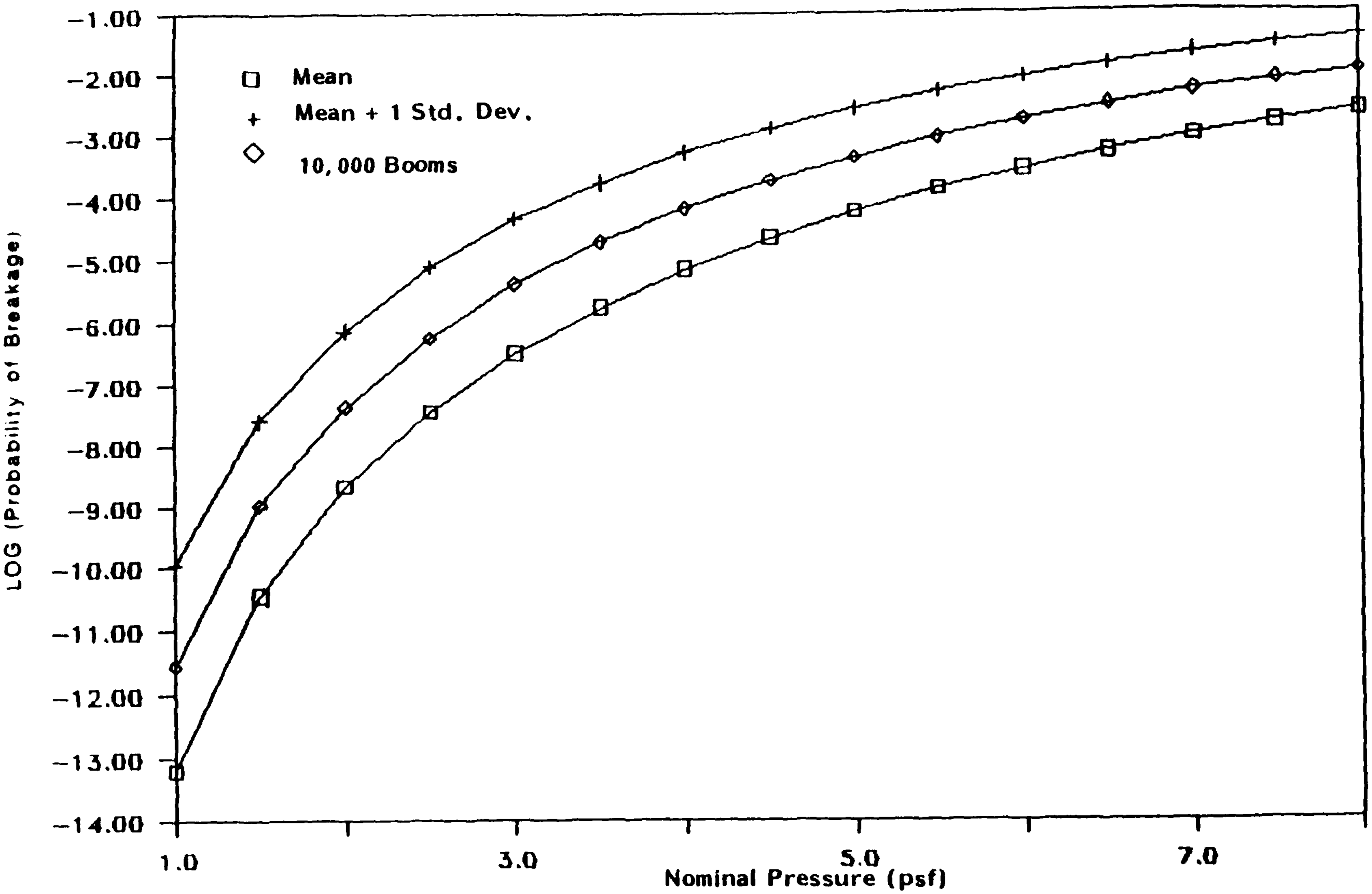

Figure 5-1b. Example Window Breakage Probabilities for Single and Repeated N-Wave Sonic Booms.

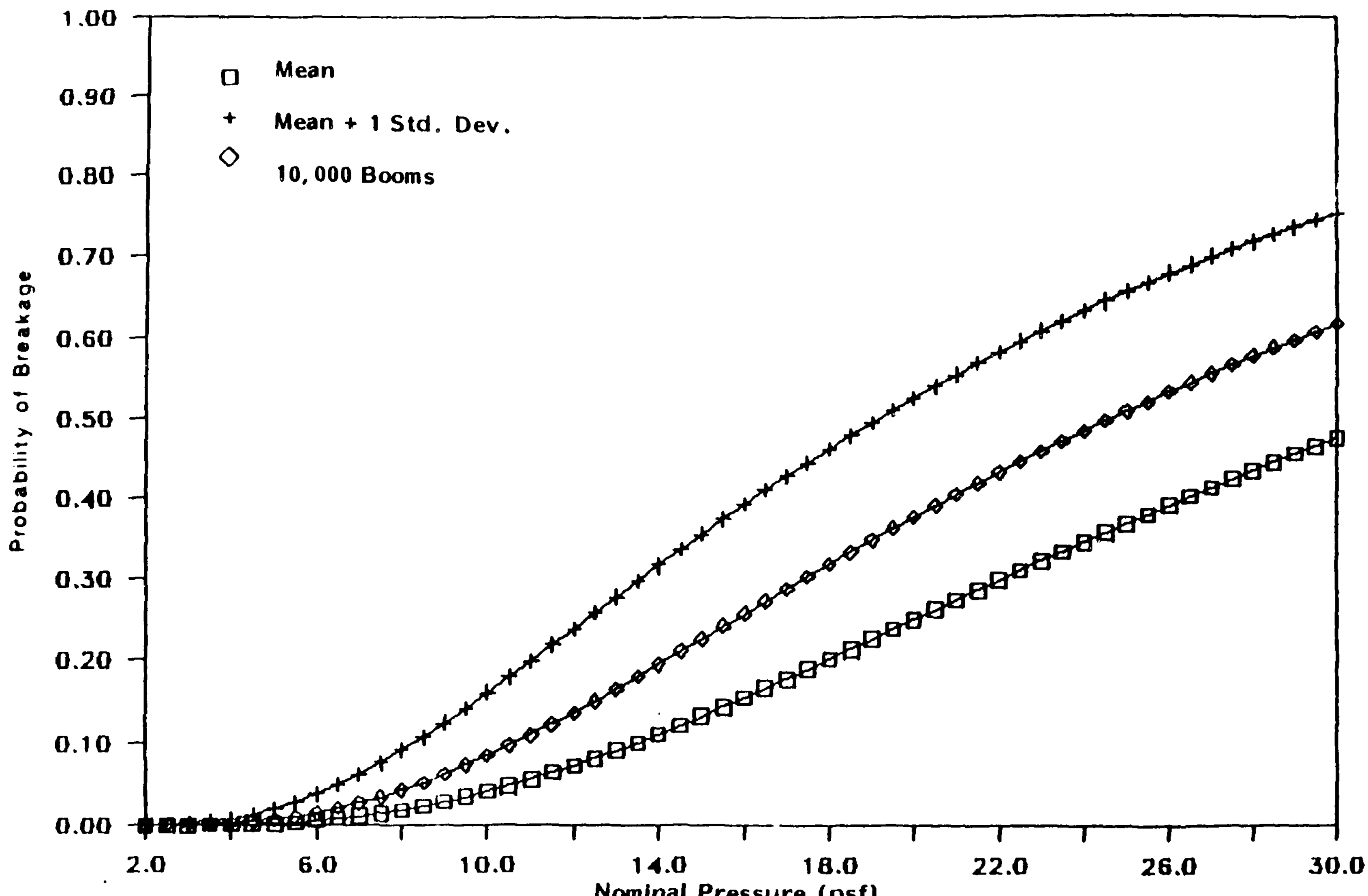

Figure 5-2a. Example Window Breakage Probabilities for Single and Repeated Focused Sonic Booms (Over Pressure Range = 2-30 psf).

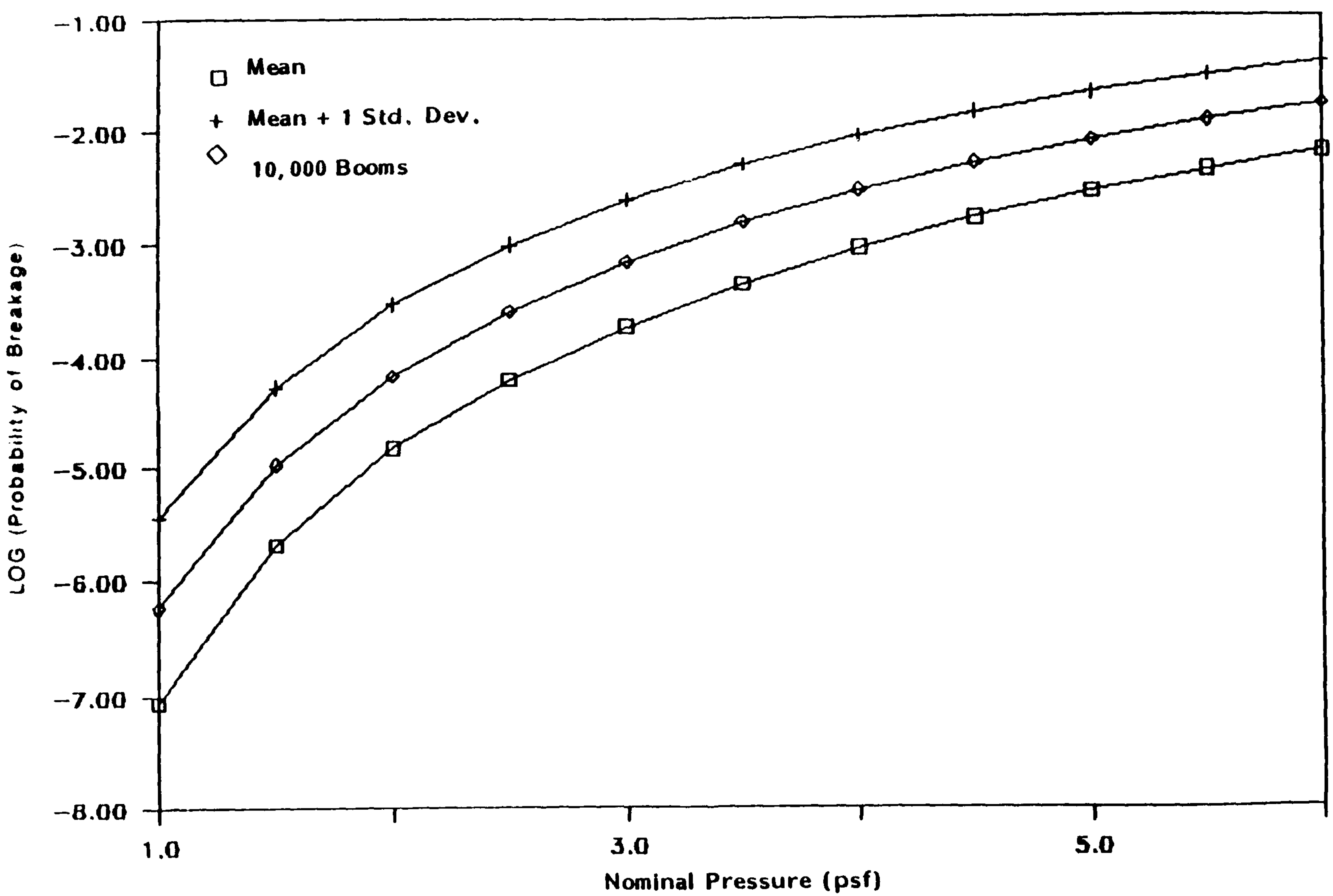

Figure 5-2b. Example Window Breakage Probabilities for Single and Repeated Focused Sonic Booms (Over Pressure Range = 1-6 psf).

5.3.1.2 Plaster Elements

To investigate the possible cumulative damage effect in the plaster elements, the fatigue relation determined by Leigh (22) is used to estimate the reduction in strength from the repeated boom exposures. Recall from Equation 5-2 that the fatigue relation was formulated in terms of the maximum tensile strain of the plaster. Since stress is proportional to strain and a linear response model was used for the plaster elements, the reductions in the breaking pressures for the plaster elements proposed in Reference 1 are estimated by scaling from the reductions in the maximum strain capacities obtained from Leigh's fatigue relation. The fatigue relation also was developed for a constant load and response amplitude for each applied load cycle. Thus, the reduced element capacities are estimated using the assumption of a constant amplitude overpressure for a given number of exposures.

First, consider the plaster ceiling model. Using Leigh's fatigue relation, the tensile strain capacities for 1,000 and 10,000 load cycles are respectively 81 and 75% of the initial tensile strain capacity. Therefore, the breaking pressures for 1,000 and 10,000 boom exposures are estimated to be 81 and 75% of the initial single exposure breaking pressure of the ceiling. Table 5-4 shows the variation of the predicted breaking pressures for the ceiling model as a function of the number of sonic booms. As was done in the preceding section for the window example, the load history of the ceiling is assumed to be defined by the number of exposures and the corresponding pressure shown. For the 10,000 boom case, it is assumed that the ceiling has survived 9,999 booms each at 14.2 psf and that the breaking pressure for the next exposure is 14.2 psf. This interpretation is consistent with the data and the formulation of the fatigue relation. The value of 14.2 psf can be interpreted as the mean estimate of the effective

applied/external sonic boom load level that the ceiling could withstand for up to 10,000 load cycles before failing.

This approach allows for the single event and the repeated exposure cases to be compared. The damage probabilities are compared for the ceiling with two different breaking pressures corresponding to the single event case at 19 psf and the 10,000 boom case at 14.2 psf.

Table 5-4 Predicted Mean Breaking Pressures for Plaster Ceilings for Repeated Sonic Booms

No. of Sonic Booms	P_G (psf)	log (P_G)
1	19.0	1.265
1,000	15.4	1.171
2,000	15.0	1.161
5,000	14.5	1.146
10,000	14.2	1.136

The recommended parameter values for the single event boom damage model are shown in Tables 5-5a and 5-5b for N waves and focused waves, respectively. The DAF values correspond to the wave duration interval of 0.10 to 0.15 sec.

Table 5-5a <u>**Statistics for Plaster Ceilings for N-waves**</u>

	Mean	Variance	Uncertainty
log (P_G)	1.265	3.24×10^{-2}	9.30×10^{-3}
log (P_e/P_f)	-0.1609	--	2.90×10^{-3}
log (P_f/P_o)	-0.0753	4.0×10^{-3}	--
log (DAF)	0.1691	7.06×10^{-3}	2.62×10^{-3}

Table 5-5b <u>**Statistics for Plaster Ceilings for Focused Waves**</u>

	Mean	Variance	Uncertainty
log (P_G)	1.265	3.24×10^{-2}	9.30×10^{-3}
log (P_e/P_f)	-0.1609	--	2.90×10^{-3}
log (P_f/P_o)	0.0471	4.46×10^{-2}	--
log (DAF)	-0.0304	9.90×10^{-3}	1.31×10^{-2}

Figure 5-3a shows the comparison of the breakage probabilities for N waves. The single event case (mean and mean plus one standard deviation statistics) is compared with the modified case for 10,000 booms. The probabilities for the 10,000 boom case are just slightly greater than the mean plus one standard deviation uncertainty case. Figure 5-3b shows the log of the probabilities over the low overpressure range. Figures 5-4a and 5-4b show similar graphs for focused booms. In the case of the focused booms, the probabilities for the 10,000 boom case are close to, but less than, the one standard deviation uncertainty predictions. The damage predictions after the repeated booms are on the order of the uncertainty of the single event

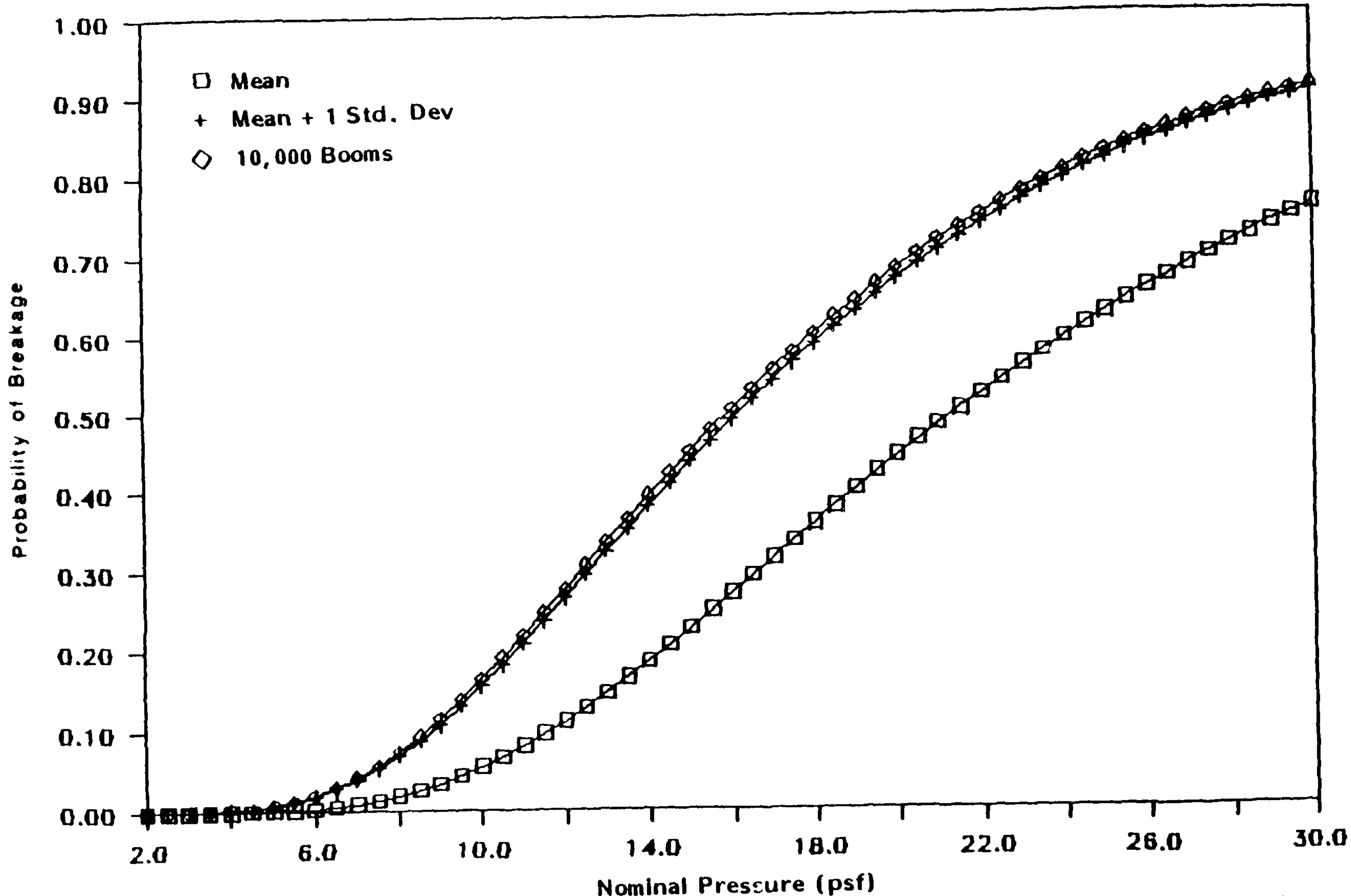

Figure 5-3a. Plaster Ceiling Cracking Probabilities for Single and Repeated N-Wave Sonic Booms (Over Pressure Range = 2-30 psf).

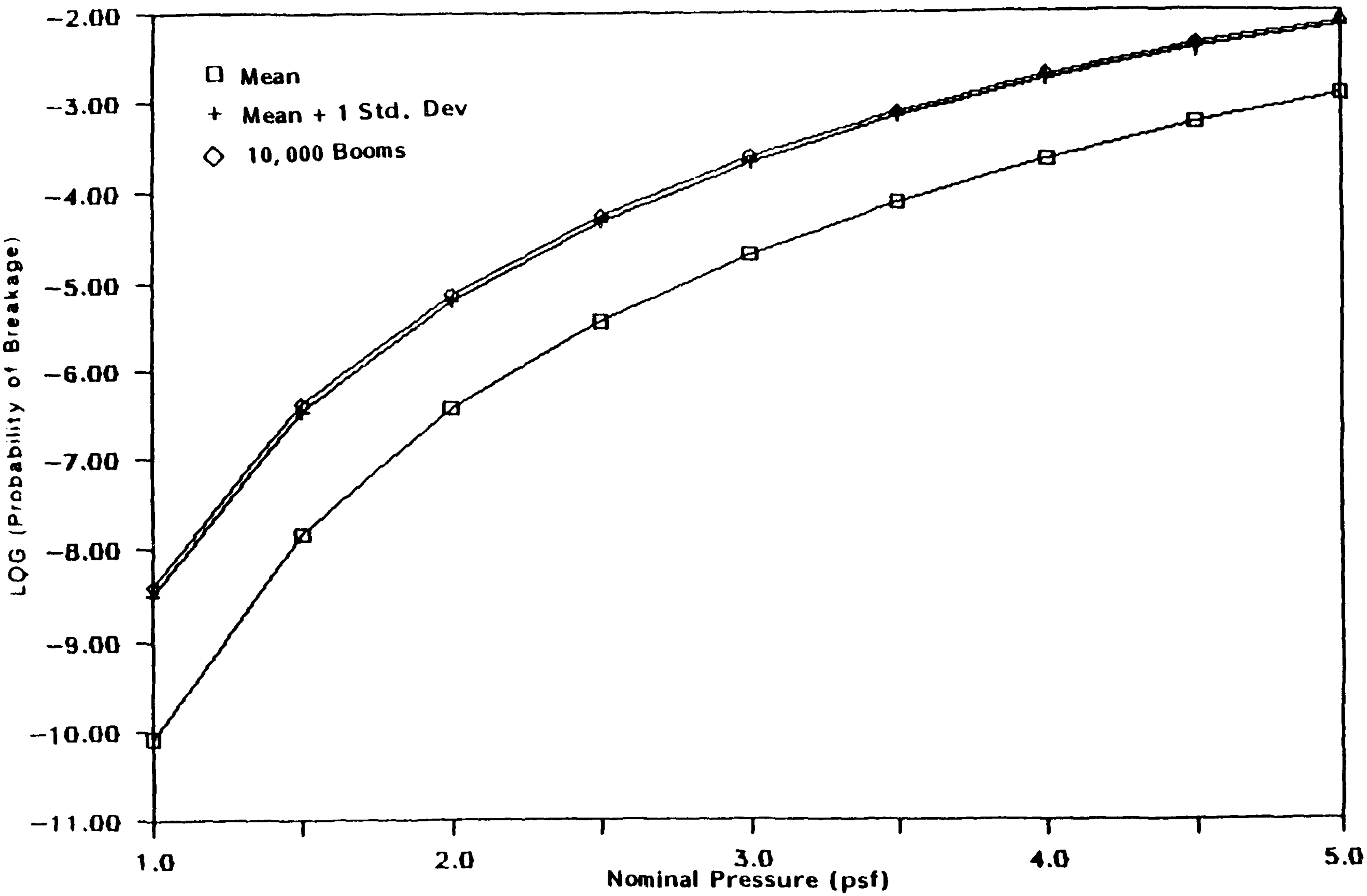

Figure 5-3b. Plaster Ceiling Cracking Probabilities for Single and Repeated N-Wave Sonic Booms (Over Pressure Range = 1-5 psf).

predictions. No clear cumulative damage effect which is significant with respect to the single event damage prediction results from Leigh's fatigue relation.

Next, consider a wood stud plaster wall element as described in Reference 1. The breaking pressure for the single event case is 48 psf. Table 5-6 shows the variation of the predicted breaking pressures with the number of boom exposures estimated using Leigh's fatigue relation. The reduced element capacities are estimated in the same manner as for the ceiling model. For the 10,000 boom case, the wall is assumed to have withstood 9,999 booms at 35.8 psf and that the breaking pressure for the next boom is also 35.8 psf. This assumption allows for the repeated boom case to be compared with the single event exposure. That is, the damage probabilities are compared for a single exposure for the wall using two different breaking pressures: first, the single exposure case with a breaking pressure of 48 psf, and second, with a reduced breaking pressure of 35.8 psf to represent the existing load history.

Table 5-6 Predicted Mean Breaking Pressures for Wood Stud Plaster Walls for Repeated Sonic Booms

No. of Sonic Booms	P_G (psf)	log (P_G)
1	48.0	1.665
1,000	38.9	1.573
2,000	37.9	1.562
5,000	36.7	1.549
10,000	35.8	1.538

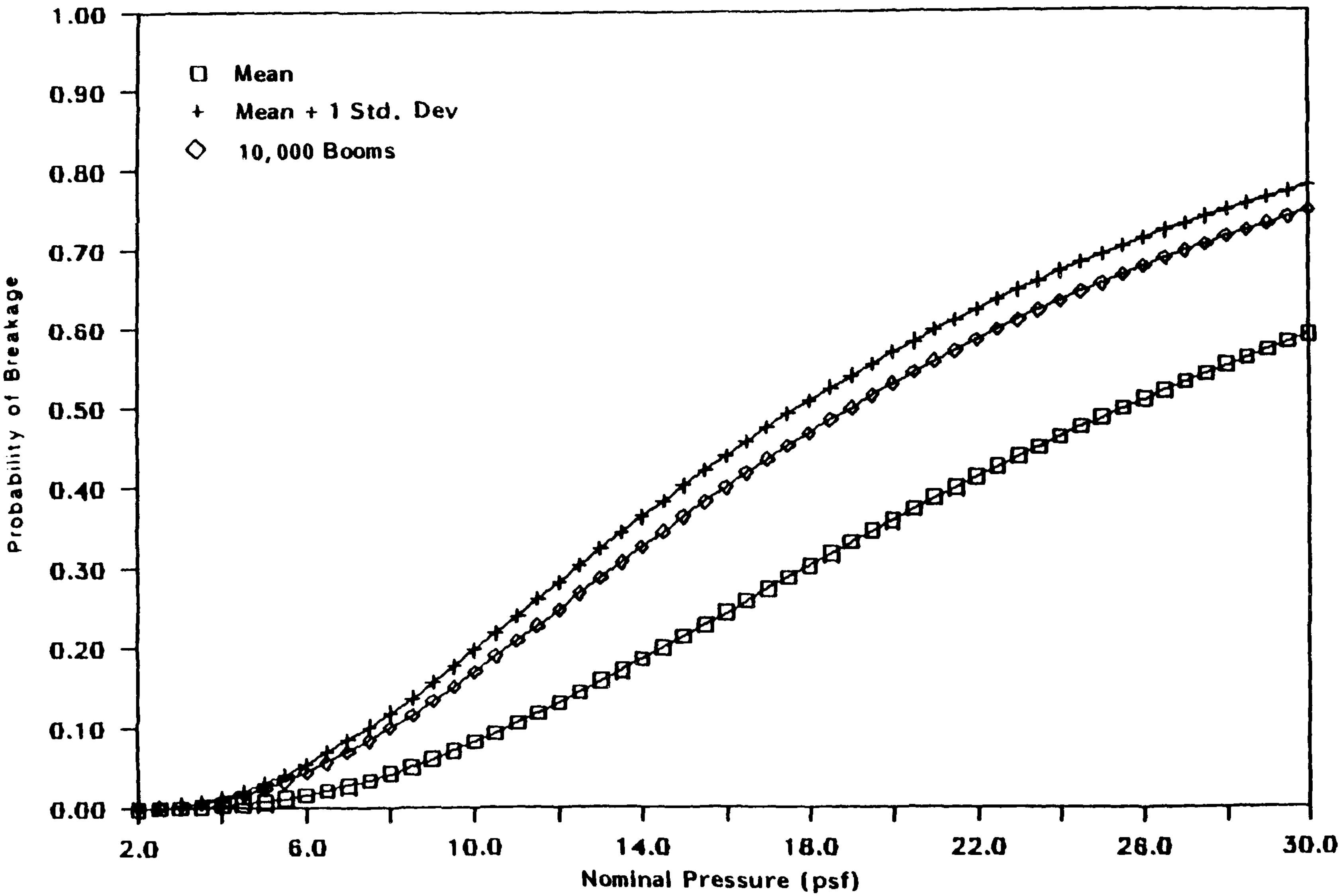

Figure 5-4a. Plaster Ceiling Cracking Probabilities for Single and Repeated Focused Sonic Booms (Over Pressure Range = 2-30 psf).

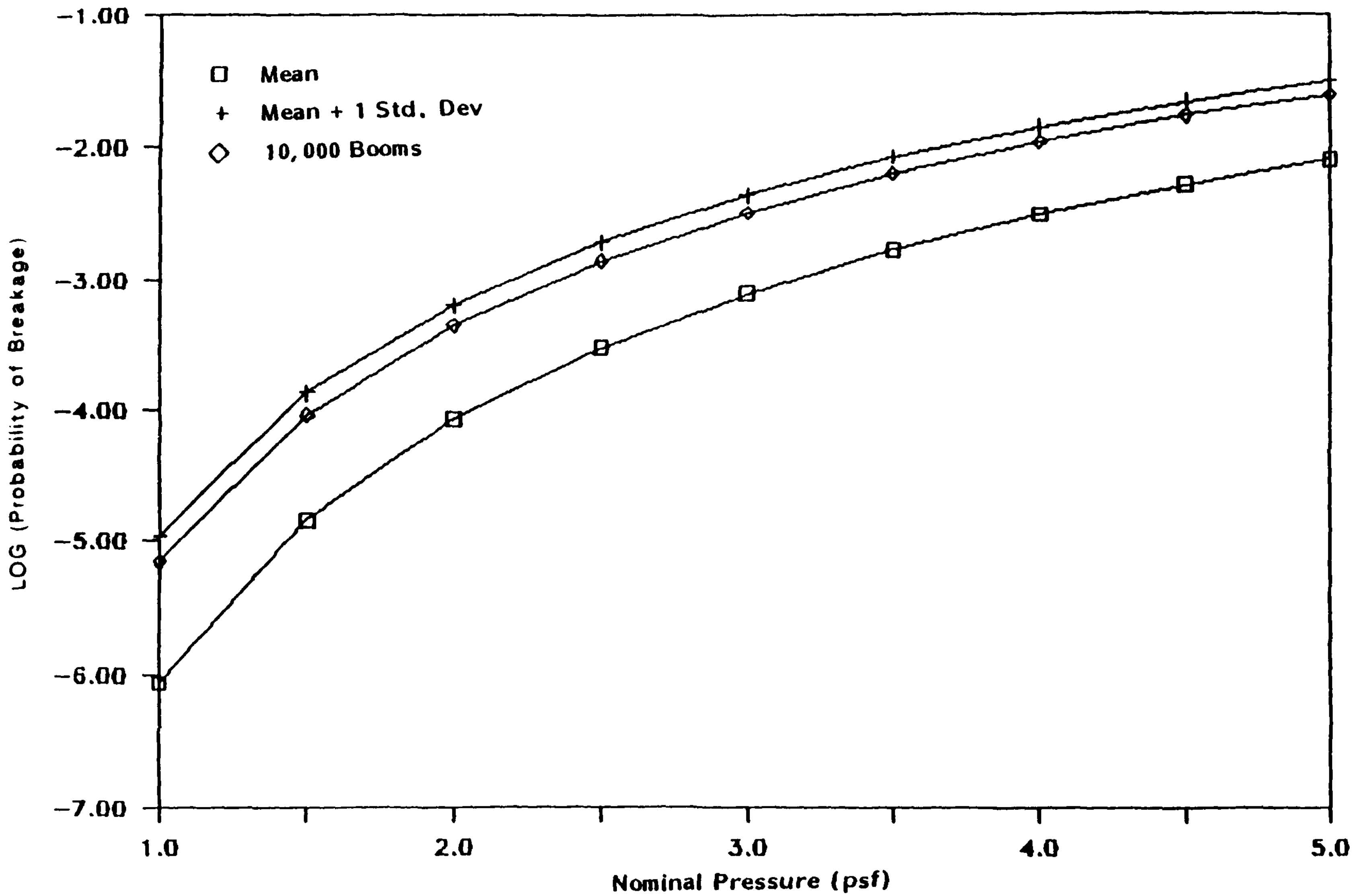

Figure 5-4b. Plaster Ceiling Cracking Probabilities for Single and Repeated Focused Sonic Booms (Over Pressure Range = 1-5 psf).

The recommended statistics from Reference 1 for the single event damage prediction are shown in Tables 5-7a and 5-7b for N waves and focused waves, respectively. The DAF values shown correspond to a wave duration interval of 0.10 to 0.15 sec.

Table 5-7a <u>Statistics for Wood Stud Plaster Walls for N-waves</u>

	Mean	Variance	Uncertainty
log (P_G)	1.665	3.24×10^{-2}	2.40×10^{-3}
log (P_e/P_f)	-0.1251	--	4.39×10^{-2}
log (P_f/P_o)	-0.0753	4.0×10^{-3}	--
log (DAF)	0.2139	2.36×10^{-3}	4.38×10^{-5}

Table 5-7b <u>Statistics for Wood Stud Plaster Walls for Focused Waves</u>

	Mean	Variance	Uncertainty
log (P_G)	1.665	3.24×10^{-2}	2.40×10^{-3}
log (P_e/P_f)	-0.1251	--	4.39×10^{-2}
log (P_f/P_o)	0.0471	4.46×10^{-2}	--
log (DAF)	0.0641	1.11×10^{-2}	1.77×10^{-2}

The breakage probabilities for the 10,000 boom case are compared with the mean and mean plus one standard deviation uncertainty cases for the N wave single event loading in Figures 5-5a and 5-5b. The single event probabilities are evaluated using the values given in Table 5-7a. The 10,000 boom damage

probabilities are evaluated using the breaking pressure value given in Table 5-6, with the other parameters in the damage model remaining the same as for the single event case. In both figures, the 10,000 boom damage probabilities fall within the one standard deviation uncertainty. For the higher overpressures, the uncertainty of the single event damage predictions substantially increases the probabilities. The dominant uncertainty term comes from the description of the load in the log (P_e/P_f) term. Similar results are also observed for focused waves as shown in Figures 5-6a and 5-6b.

Reviewing the results shown in Figures 5-3 to 5-6, the damage predictions after 10,000 boom exposures are within the range of uncertainty of the single event predictions. The predictions for the repeated boom case are based on the assumption that the fatigue relation developed by Leigh is valid. However, considering that the fatigue relation was derived from very limited data and that the damage predictions fall within the uncertainty of the single boom predictions, the evidence for a cumulative damage effect in the plaster is weak. A well-founded cumulative damage model for plaster cannot be recommended.

5.3.2 Comparison with Environmental Effects

In the literature review, we found that the influences of the environmental conditions can be substantial with regard to observed damage. We concluded that the cumulative damage effect is small with respect to the damage from environmental loading. In addition, there is some evidence that the sonic boom loading may act to relieve stresses due to environmental forces.

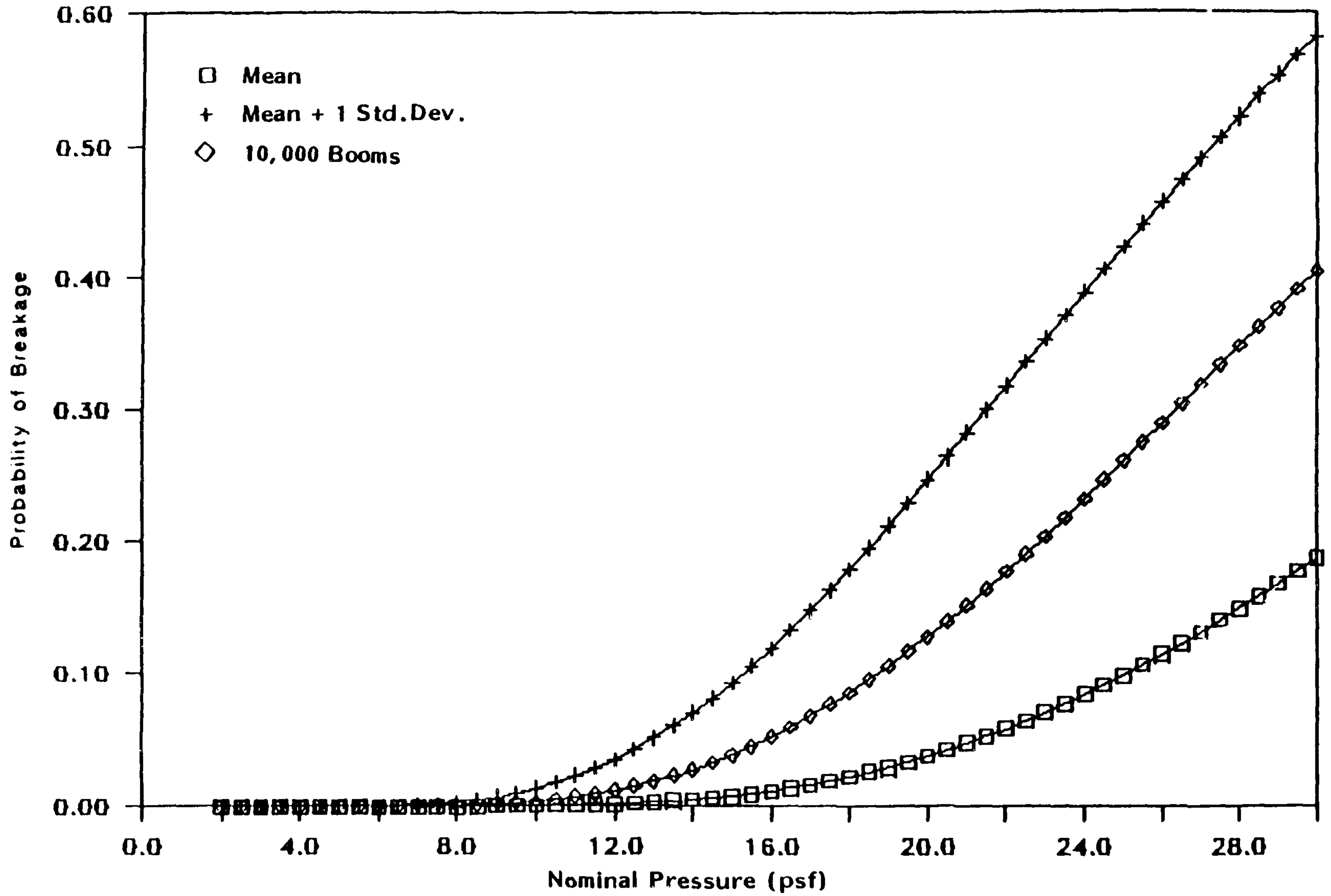

Figure 5-5a. Wood Stud Plaster Wall Cracking Probabilities for Single and Repeated N-Wave Sonic Booms (Over Pressure Range = 0-30 psf).

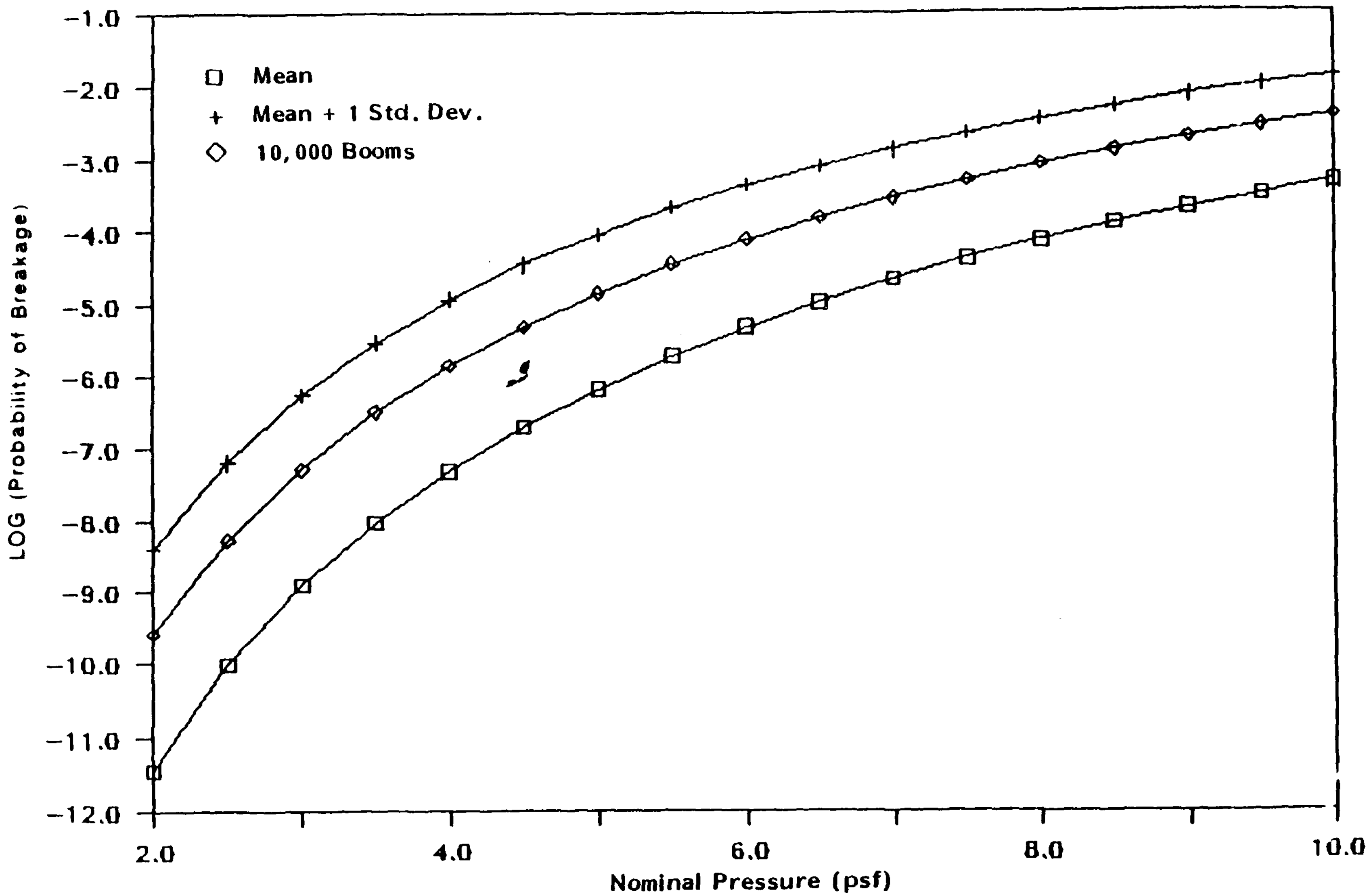

Figure 5-5b. Wood Stud Plaster Wall Cracking Probabilities for Single and Repeated N-Wave Sonic Booms (Over Pressure Range = 2-10 psf).

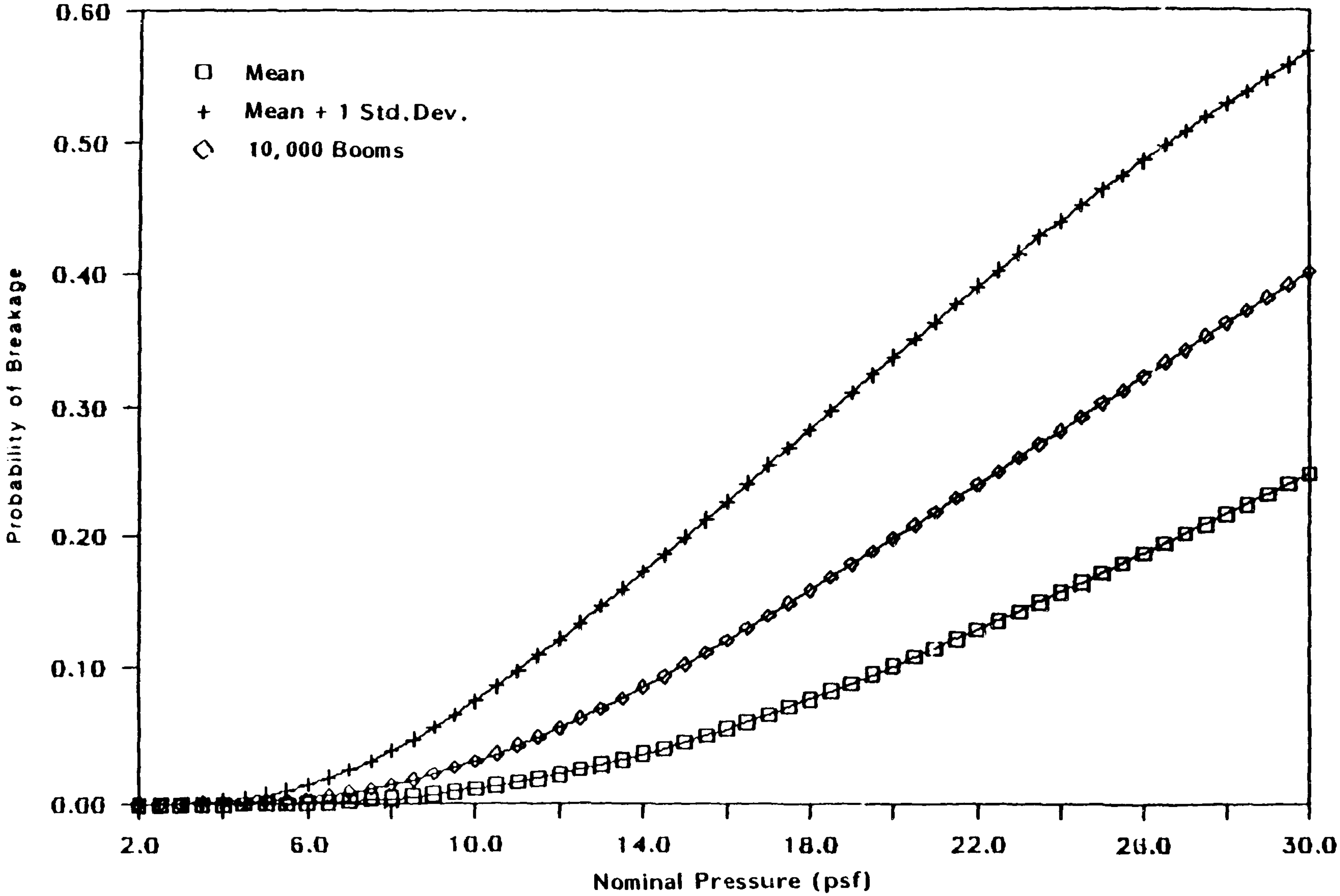

Figure 5-6a. Wood Stud Plaster Wall Cracking Probabilities for Single and Repeated Focused Sonic Booms (Over Pressure Range = 2-30 psf).

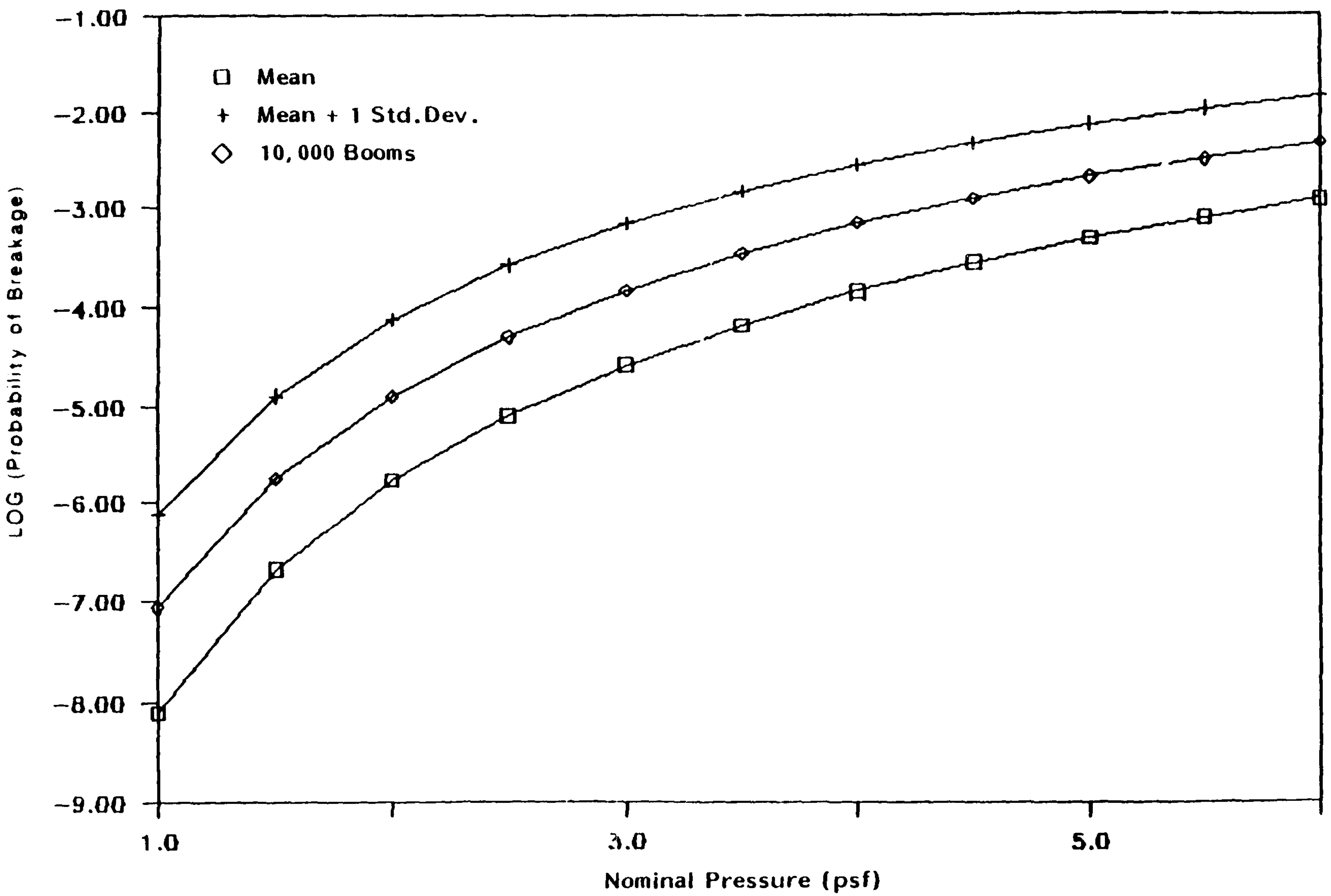

Figure 5-6b. Wood Stud Plaster Wall Cracking Probabilities for Single and Repeated Focused Sonic Booms (Over Pressure Range = 1-6 psf).

From the White Sands tests, Wiggins (13, 14) found that the cracking threshold overpressures for plaster elements were below the "noise" level from the environmental conditions. From the crack measurement data, the cracking rates during the boom exposure periods did not exceed the cracking rates during the ambient conditions until the average overpressures were greater than about 10 psf. In addition, at overpressures less than about 3 psf, the data indicated that the cracking rates during the boom exposures were less than those during the ambient conditions. Wiggins (18) concluded that the transient sonic boom response at low overpressures acted to relieve some of the stress induced by temperature, humidity, and settlement, rather than cause damage itself.

The estimated cumulative damage thresholds derived from the White Sands tests were on the order of 10 to 12 psf. These thresholds were estimated from the cracking rate study as the overpressure level at which the boom period cracking exceeded the ambient cracking rate. It could be inferred from these values that the effects of the environment were approximately equivalent to booms with nominal overpressures of 10 psf. Similarly, from the blast tests discussed in Reference 17, the fluctuations of temperature and humidity induced strains in plaster walls which were greater than those produced by the minimum ground vibration damage threshold.

The natural aging processes of building materials will lead to some irreversible damage. Shrinkage occurs in plaster as part of the curing process as water evaporates from the mix. While most of the shrinkage will occur initially over a relatively short period, the process is continuous through time and shrinkage cracks are an inevitable outcome. Shrinkage can also occur in improperly cured lumber. This shrinkage can result in observable warping in wood members and lead to

additional stresses in plaster elements. Window putty will dry, become brittle, and may crumble over time.

Temperature and humidity variations also will lead to some degradation in the integrity of glass and plaster. High moisture levels can weaken the bond of plaster and stucco to the lath. If moisture gets inside a wood stud wall, fungus and mildew can develop, eventually leading to rot. Daily and seasonal fluctuations in temperature and humidity produce a cyclic loading effect. Depending on the coefficient of thermal expansion of the material, temperature changes can cause cracks to open and close. Since a building is composed of several different materials, some differential strains can develop due to the different thermal expansivities of the materials. In glass, temperature and humidity fluctuations can cause surface flaws to grow, progressively weakening the glass pane.

The damaging effects of the environmental factors are greater than those induced by sonic booms. At low overpressures, the environmental forces are more severe than those from the booms. If there is a cumulative damage effect associated with low overpressures, it will be less significant than from natural effects. Over its life, a building will be subjected to more cycles of temperature and humidity fluctuations than sonic booms. Each sonic boom produces a short-lived transient response which does not induce permanent deformations in the building, excluding the case for window breakage. However, long-term natural phenomena can result in permanent distortions in the building as well as other irreversible effects.

6. ASAN MODEL FOR DAMAGE TO CONVENTIONAL STRUCTURES

6.1 Introduction

The ASAN model for damage to conventional structures is built upon the framework developed by Hershey and Higgins as outlined earlier in this report. This model has been enhanced based upon the results of the critical review and sensitivity study. Damage estimates are developed for windows, plaster elements (walls and ceilings), and bric-a-brac based upon predicted ground levels of sonic booms and the geographical distribution of the conventional structures in the affected area by assessing the probability that the load applied to these elements will exceed their capacity. Although the calculations within ASAN are in terms of these structural elements, the environmental planner is able to characterize an area of concern in terms of standard categories of structures used for planning purposes. The ASAN model accepts these descriptors, translates them into numbers of windows, ceilings, walls, and pieces of bric-a-brac of different types, and reports anticipated damage in terms of the anticipated damage to these elements.

Damage assessments are expressed in terms of the probability of damage to windows, ceilings, plaster walls, and bric-a-brac. Damage statistics are generated at several levels: an aggregate overview report identifies the total anticipated damage from a proposed set of supersonic operations. In addition, more detailed reports can be generated which show the locations where damage is expected and the distribution of structural impact among the standard structural planning categories (see Table 6-1).

This section begins with a presentation of the categories of conventional structures which have been incorporated into ASAN, a characterization of these categories in terms of vulnerable

elements, and a definition and characterization of the categories of vulnerable elements. This section is followed by a subsection which presents the logic ASAN employs for assessing structural damage from sonic loads. The third subsection contains a detailed development of the damage probability model and the statistics which have been implemented in this model. The final subsection contains a brief discussion of the provisions made for future enhancements and refinements.

6.2 ASAN Categories of Conventional Structures

One of the first steps an environmental planner must take in considering a proposed action is characterizing the existing, affected environment. This characterization must be consistent from planner to planner and assessment to assessment. The requirement for consistency is derived from NEPA regulations for traceability of the environmental impact assessment process and the need for public accountability. To achieve the desired consistency, the standard categories used for planning purposes have been adapted to this purpose. These categories and the modifications are shown in Table 6-1.

To use this system, the planner will identify the built environment by specifying structure types in terms of the ASAN category and applicable category parameters (if any) and the locations of the structures. The ASAN system will automatically interpret the specification of these structures in terms of structural elements (windows, plaster ceilings and walls, and bric-a-brac) vulnerable to sonic boom. The planner will not need to specify the complement of these elements in these structures, but the planner will have the capability of examining their definitions and adding special purpose categories should unusual situations need to be considered.

Table 6-1 ASAN Structural Categories

Planning Category	ASAN Category	Category Parameters
Residential	Single family dwellings	
	Mobile homes	Exterior walls (wood or metal)
	Multi-family dwellings	Number of units
Schools	Schools	Number of classrooms
Churches	Churches	
Hospitals	Hospitals	Number of beds
Office buildings	Office buildings	Number of floors
Commercial buildings	Commercial buildings	

The element definitions which have been incorporated into ASAN are intended to be representative of construction in the southwestern region of the United States. These definitions were derived from a very brief survey of the region around Edwards AFB and crossverified with a previous study of residential window populations in the vicinity of Vandenberg AFB, California (8). As use of the system is extended, it may be necessary to add regional modifiers for other sections of the country and to refine the category definitions for the southwestern region with a more extensive survey.

Two levels of structural element categories have been defined. The top level categories (windows, plaster ceilings, plaster walls, and bric-a-brac) are used for reporting the anticipated damage from a proposed series of supersonic operations. A more refined set of categories of structural elements has been developed for purposes of analysis within

ASAN. The window and plaster element categories are described in the following subsections. The structural elements are then used to define the structural categories.

6.2.1 Window Categories

To describe the window population five categories and two glass pane conditions have been defined. The categories have been selected based upon window size, following previous studies on blast effects on windows (12). Glass panes are further divided into those in good condition and those which have been preweakened by stress raisers or existing damage. The size categories are defined in terms of the exposed areas of the windows, as shown in Table 6-2. A range of areas is defined for each category. The typical expected glass thickness for each category is also shown in this table.

Combining the defined dimensional characteristics with estimates of the aspect ratios for the windows, the natural frequencies for each category were computed for each category. These computations are shown in the table. A simply supported plate model was used to evaluate the frequencies. However, recognizing that the support conditions for windows are neither simply supported nor clamped but rather an intermediate condition, the upper bound frequencies were extended to include the cases of clamped support. Also shown in this table is a representative frequency for each category which will be used to establish the appropriate DAF values for that category.

Table 6-2 Categories of Windows

Category	Area Range ft^2 (m^2)	Thickness in. (cm)	Natural Frequency (Hz)	Representative Frequency (Hz)
A	0.00 - 2.00 (0.00 - 0.61)	3/32 (.238)	80 - 175	95
B	2.00+ - 10.00 (0.61+ - 3.05)	3/16 (.476)	30 - 140	60
C	10.00+ - 50.00 (3.05+ - 15.24)	1/4 (.635)	8 - 45	18
D	50.00+ - 100.00 (15.24+ - 30.50)	5/16 (.794)	5 - 14	6
E	>100.00 (>30.50)	5/16 (.794)	2 - 7	4

Table 6-3 presents the parameters for the static breaking pressures of good quality glass panes in each of the 5 window categories. The breaking pressure was evaluated for the typical representative area for each category in three steps. First, the Libby-Owens-Ford formula was used to determine the 60-sec breaking pressure for a new glass pane. To include the loss in strength associated with aging, an average strength reduction of 50% is used. The influence of the short-duration sonic boom loading is included by increasing the breaking pressure through the PPG duration scaling formula using a nominal load duration of 0.1 sec (a typical sonic boom duration for a fighter aircraft). These results are presented in Table 6-3. The statistics for the preweakened glass panes differ only in the mean breaking pressure. Following Hershey and Higgins, the mean breaking pressure for a preweakened glass pane is one-tenth of that for the corresponding glass pane in good condition.

Table 6-3 Baseline Glass Breaking Pressure Statistics

Category	Representative Area ft^2 (m^2)	Breaking Pressure (psf)	Mean (LOG P_G)	Variance of (LOG P_G) Among Category Members
A	1.0 (.305)	539	2.706	0.0227
B	4.5 (1.372)	349	2.522	0.0136
C	22.0 (6.706)	111	2.024	0.0136
D	71.0 (21.64)	48.5	1.670	0.0025
E	120.0 (36.58)	28.7	1.437	0.0139

Sixty sec breaking pressure uncertainty:
VAR (LOG P_G) = 0.0263

Strength reduction uncertainty (used vs. new glass):
VAR (LOG P_G) = 0.0142

Application of these results requires an adjustment from the nominal load duration shown in this table to the actual load duration. Looking ahead to the load duration intervals which will be employed in ASAN, Table 6-4 shows the breaking pressure load duration adjustment factors. These factors are included in the ASAN structural effects calculation module.

Table 6-4 <u>Factors for Adjusting Breaking Pressures for Load Duration</u>

Mean Duration (sec)	Multiply Breaking Pressure By	Add to Log(P_G)
0.07	1.02	0.0086
0.12	0.99	-0.0044
0.19	0.96	-0.0177
0.30	0.93	-0.0315

Three types of variances are presented in Table 6-3. The first variance is the uncertainty in the 60-sec strength of the used glass pane. From the limited number of samples tested at Texas Tech, the results indicate that the coefficient of variation of the 60-sec breaking pressure is typically 0.25. This value is adopted for evaluating the variance of log(P_G). The second type of variance is a measure of the range of values of the breaking pressure within each window category. Recall that the 60-sec breaking pressure is dependent on the area of the glass pane. Considering a range of areas within each category results in a range of breaking pressures. The third type of variation is a result of the uncertainty of the relative strength of used glass as compared to new glass. The Texas Tech data indicated a range of reduction factors from 40% to 60%. Since it is not known that this is the full range of values, a variance was calculated by assuming that the range from 25% to 75% accounts for 90% of the possible values.

6.2.2 Plaster Element Categories

Plaster is generally applied as an interior finish for ceilings and walls in structures. Categories of plaster elements were selected which are representative of typical systems in the exposed population. Since plaster finishes are used together with a supporting structural system (e.g., ceiling joists or wall studs), the plaster elements are defined in terms of the type of support structure employed.

The plaster element categories are:

A. Wood framed ceiling - 2 in. x 6 in. (5.08 cm x 15.24 cm) wood ceiling joists spaced at 16 in. (40.64 cm) on center with 1/2 in. (1.27 cm) thick plaster ceiling finish.

B. Wood frame wall - 2 in. x 4 in. (5.08 cm x 10.16 cm) wood studs spaced at 16 in. (40.64 cm) on center, plywood sheathing and stucco or wood siding exterior, with 1/2 in. (1.27 cm) thick interior plaster finish.

C. Brick masonry wall - 4 in. (10.16 cm) thick brick masonry with 1/2 in. (1.27 cm) thick interior plaster finish.

D. Metal stud partition wall - 3 5/8 in. (8.25 cm) deep steel studs spaced at 16 in. (40.64 cm) on center with 1/2 in. (1.27 cm) thick plaster finish on each side.

Categories A, B, and C are typical configurations for residential structures. The walls of categories B and C represent exterior walls. Category D represents a partition wall commonly occurring in commercial buildings. As for glass,

the ASAN model provides for plaster in good condition as well as plaster which has been previously weakened.

Wiggins (13) developed maximum safe predicted overpressures for new and old gypsum board as 16 and 5.4 psf respectively, based upon the White Sands test results. These overpressures are associated with small hairline cracks. These overpressures correspond to three standard deviations below the mean. Wiggins used a coefficient of variation of 0.33 for these overpressures. Use of this coefficient resulted in mean overpressures for minor damage of 32 and 9 for the new and old gypsum board. Assuming the ratio of new material strength to old material strength is indicative of the ratios of good plaster strength to predamaged plaster, the mean strength of predamaged plaster has been taken to be 30% of that of good plaster with the same uncertainty in strength.

The damage to the plaster elements is associated with diaphragm behavior. That is, the out-of-plane bending of the elements is considered and the critical stress is the maximum tensile bending stress in the plaster. Racking failures are not included because they are considered to be less critical than the diaphragm failures. At a given overpressure, an in-plane shear or racking failure requires a much greater input of elastic energy to the structural element than that for a diaphragm failure. As a result, the plaster cracking due to diaphragm response is considered to be more critical.

For all of the categories, the simply supported beam model was used as the basic response model to evaluate the natural frequencies and the maximum stress in the plaster. Table 6-5 shows the representative span dimension and a computed range of frequencies for each category. For the ceiling, the span refers to the horizontal length of the ceiling joists. Although the span may vary depending on the size of the rooms in the house,

the 12 ft (3.658 m) span is selected as a representative dimension for this type of ceiling system. For the walls of categories B, C, and D, the spans reflect the most commonly occurring wall heights in each category.

Table 6-5 Plaster Elements

Category	Type	Span ft (m)	Natural Freq. Range (Hz)	Representative Frequency (Hz)
A	Ceiling	12.0 (3.66)	12 - 22	16
B	Wood frame wall	8.0 (2.44)	30 - 35	31
C	Brick wall	8.0 (2.44)	25 - 40	27
D	Partition wall	10.0 (3.05)	24 - 27	25

The natural frequencies appearing in Table 6-5 were computed using the expression for a simply supported beam.

$$f = \{ \pi [E I / m]^{1/2} \} / 2 L^2 \qquad (6\text{-}1)$$

where L = span

E = modulus of elasticity (for the plaster)

I = moment of inertia of the beam cross section (based on an "E weighted" composite of the wood and plaster areas)

m = mass per unit length

For each category in Table 6-5, an expected range of frequencies as well as a single representative frequency is presented. In the case of the ceiling, the frequency range represents the variation due to differences in the span of the ceiling joists.

For instance, the joists may span across a room having a length between 9 and 14 ft (2.74 and 4.27 m). For the walls of categories B and D, since story heights are fairly standard in the types of structures where these elements occur, the range of natural frequencies is due to the differences in the unit weights of the materials which may be employed. A wider frequency range is shown for the brick wall of category C. In some cases with this type of construction, the boundary condition at the base of the wall is better represented by a clamped support rather than a simple pinned support. The upper-bound natural frequency reflects the effect of the clamped support.

Table 6-6 presents the static breaking pressures and the associated statistics for each of the plaster element categories. The breaking pressures correspond to the applied pressure required to initiate cracking in the plaster. The maximum tensile stress at which cracking occurs is taken to be 150 psi. Reviewing data on plaster strength, Hershey and Higgins reported that the tensile strength of plaster may vary between 100 and 350 psi, depending on the type of plaster and the mix. Considering that the strength of plaster can deteriorate due to aging, humidity, and temperature effects, the value of 150 psi is adopted here as a representative value for in-service plaster. The simply supported beam model is used to relate the maximum plaster tensile stress to the applied breaking pressure.

Table 6-6 Plaster Breaking Pressures

Category	P_G (psf)	Mean (LOG P_G)	Variance of (LOG P_G) Among Category Members
A	19	1.265	0.0093
B	48	1.665	0.0024
C	48	1.665	0.0034
D	25	1.382	0.0028
VAR (LOG P_G) = 0.0324			

As for windows, two types of variances are presented for the plaster elements. The variance of the logarithm of the breaking pressure is the value used by Hershey and Higgins. Because there are no data on the probability distribution of the strength of plaster, Hershey and Higgins needed to identify a proxy set of probability data. Using the argument that the factors influencing the variability in plaster strength are similar to those affecting the strength of mortar, the variance of the logarithm of the breaking strength of mortar is used to represent that of plaster.

Systematic variations in the plaster breaking pressure due to the variations in the span length of the elements within each category result in the second type of variance. Since the breaking pressure is dependent on the span of the element, a range of span lengths has associated with it a range of breaking pressures. Increasing the span has the effect of reducing the breaking pressure, while decreasing the span increases the breaking pressure. Notice that the variance among members of a category is more than a factor of 10 smaller than the

uncertainty in the strength of the plaster. This variance contrasts with the statistics for windows. For windows the variability within a category was comparable to the uncertainty in the glass breaking pressure.

6.2.3 Relationship of Structural Categories and Elements

To develop the building element exposure model, estimates were made of the mean and variance of the number of each element type expected in each of the ASAN building categories. The mean and variance estimates were derived from data obtained in a field survey of the area near Edwards AFB combined with the judgment of the authors. For the window estimates, additional data were obtained from a window pane survey conducted in the communities near Vandenberg AFB (8). Because these statistics have been based upon judgment and on a very limited sample they are not definitive, but at the present time, they represent best estimates. Tables 6-7 through 6-22 present these statistics.

Table 6-7 Mean and Variance Estimates for the Number of Windows by Window Category for Mobile Homes

Category	Mean	Variance
A	5	1
B	13	12.2
C	0.5	0.06
D	0	0
E	0	0

Table 6-8 Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Mobile Homes

(Only for mobile homes with wood frame construction. No plaster elements for mobile homes with sheet metal exteriors.)

Category	Mean	Variance
A	3	1
B	4	1
C	0	0
D	0	0

Table 6-9 Mean and Variance Estimates for the Number of Windows by Window Category for Single Family Dwellings

Category	Mean	Variance
A	6	1
B	15	16
C	4	4
D	0	0
E	0	0

Table 6-10 **Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Single Family Dwellings**

Category	Mean	Variance
A	5.5	1
B	7	1
C	7	1
D	0	0

Table 6-11 **Mean and Variance Estimates for the Number of Windows by Window Category for Multi-Family Dwellings**

(N = number of units)

Category	Mean	Variance
A	3N	N^2
B	9N	$6.2N^2$
C	1.9N	$0.36N^2$
D	0	0
E	0	0

Table 6-12 Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Multi-Family Dwellings

(N = number of units)

Category	Mean	Variance
A	3N	N^2
B	3N	N^2
C	3N	N^2
D	0	0

Table 6-13 Mean and Variance Estimates for the Number of Windows by Window Category for Churches

Category	Mean	Variance
A	3	1
B	30	36
C	0	0
D	0	0
E	0	0

Table 6-14 Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Churches

Category	Mean	Variance
A	6	4
B	10	9
C	10	9
D	0	0

Table 6-15 Mean and Variance Estimates for the Number of Windows by Window Category for Hospitals

(N = number of beds)

Category	Mean	Variance
A	15	6.2
B	$2N + 40$	$(0.5N + 10)^2$
C	20	5
D	0	0
E	0	0

Table 6-16 **Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Hospitals**

(N = number of beds)

Category	Mean	Variance
A	0	0
B	$0.5N + 10$	$(0.17N + 3.33)^2$
C	$0.5N + 10$	$(0.17N + 3.33)^2$
D	0	0

Table 6-17 **Mean and Variance Estimates for the Number of Windows by Window Category for Office Buildings**

(N = number of floors)

Category	Mean	Variance
A	$9N$	$12.2N^2$
B	$15N$	$25N^2$
C	11	$20.2N^2$
D	0	0
E	0	0

Table 6-18 <u>Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Office Buildings</u>

(N = number of floors)

Category	Mean	Variance
A	0	0
B	9N	$9N^2$
C	9N	$9N^2$
D	0	0

Table 6-19 <u>Mean and Variance Estimates for the Number of Windows by Window Category for Commercial Establishments</u>

Category	Mean	Variance
A	0	0
B	3	0.56
C	2	0.25
D	0.5	0.014
E	0	0

Table 6-20 Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Commercial Establishments

Category	Mean	Variance
A	2.5	0.56
B	2	0.25
C	2	0.25
D	0	0

Table 6-21 Mean and Variance Estimates for the Number of Windows by Window Category for Schools

(N = number of classrooms)

Category	Mean	Variance
A	$24N$	$64N^2$
B	$6N + 48$	$(1.2N + 10)^2$
C	0	0
D	0	0
E	0	0

Table 6-22 **Mean and Variance Estimates for the Number of Plaster Elements by Element Category for Schools**

(N = number of classrooms)

Category	Mean	Variance
A	0	0
B	$1.5N + 8$	$(0.5N + 2.67)^2$
C	$1.5N + 8$	$(0.5N + 2.67)^2$
D	0	0

Extremely limited information is available to characterize the proportion of the glass or plaster element population which is good and that which is preweakened. Following Hershey and Higgins the ASAN model assumes that 0.61% of the population of glass is preweakened, and that 99.39% is good glass. In the absence of any information to define the proportions for plaster, the model has assumed that the ratio of good plaster to predamaged plaster is approximately the same as that for glass. Thus, 99% of the plaster elements are assumed to be in good condition and 1% in a predamaged state.

Bric-a-brac is the most ill-defined class of vulnerable element with regard to both its vulnerability and the number of pieces at risk. Following Hershey and Higgins, the ASAN model uses twice the total mean number of windows in a building as an estimate of the mean number of pieces of bric-a-brac. The coefficient of variation for the number of pieces of bric-a-brac per structure is modeled as one-half (0.5).

6.3 ASAN Damage Assessment Logic

This section provides a top level view of the input, processing and output from the ASAN conventional structures damage assessment module. The discussion begins with a description of the input requirements, characterizes the module output requirements, and then describes the processing logic.

The ASAN conventional structures damage assessment module requires two types of input: a description of the affected built environment and the statistics of the loads affecting these structures. The load characterization will be addressed first.

Uncertainty in the structural effects calculations will be minimized by calculating the load statistics explicitly for each flight path of interest and each meteorological profile of interest and storing the following information for each sonic boom affecting the region: its peak overpressure, its peak-to-peak duration, and the type of waveform (N-wave or focused wave).

If system resources are adequate, the best results will be produced by analyzing the structural effects of the calculated waveforms without any aggregation or other simplification. Recognizing the present limits of personal computers, the following discussion assumes that some level of categorization of overpressure levels and boom durations will be required for implementation into ASAN. In addition, we anticipate that the propagation module will introduce additional load uncertainty by not explicitly addressing each flight profile and set of meterological conditions. Values for these additional uncertainties will not be addressed here. If the uncertainty is any greater than that resulting from the discretization, the additional uncertainty, when it has been quantified, must be added to the load uncertainties quoted. Suggested pressure and

duration categories and the effect on the uncertainty of damage estimates of using these categories is presented as part of the subsequent discussion.

The boom duration intervals will affect the uncertainty in damage estimates due to the resulting uncertainty in Dynamic Amplification Factors (DAF); use of peak overpressure intervals will contribute to the damage uncertainty through uncertainty in the nominal peak overpressure, P_o.

The recommended intervals are shown in Table 6-23. For peak overpressure intervals the table contains the resulting uncertainty in the logarithm of nominal peak overpressure. These uncertainties were derived by taking the logarithm of the ratio of the upper bound of the interval to the lower bound and regarding this value as a four sigma value. The uncertainty in the logarithms of DAF generated by using duration intervals will be presented in the discussion of DAFs.

Table 6-23 Sonic Boom Reporting Intervals

Table 6-23a Duration Intervals

Duration Interval (sec)	Mean Duration (sec)
0.05-0.10	0.07
0.10-0.15	0.12
0.15-0.25	0.19
0.25-0.35	0.30

Table 6-23b <u>Overpressure Intervals</u>

Peak Overpressure Intervals (psf)	Mean (psf)	Log (P_O) Uncertainty
0.5-2.5	1.12	3.05×10^{-2}
2.5-4.0	3.16	2.60×10^{-3}
4.0-6.0	4.90	1.94×10^{-3}
6.0-8.0	6.93	9.76×10^{-4}
8.0-10.0	8.94	5.87×10^{-4}
10.0-12.0	10.95	3.92×10^{-4}
12.0-15.0	13.42	5.87×10^{-4}
15.0-18.0	16.43	3.92×10^{-4}
18.0-21.0	19.44	2.80×10^{-4}
21.0-24.0	22.45	2.10×10^{-4}
24.0-27.0	25.46	1.64×10^{-4}
27.0-30.0	28.46	1.31×10^{-4}

The load must be characterized as the expected number of occurrences of each peak overpressure interval, duration interval and waveform (N-wave or focused wave) at each location of interest.

The ASAN structures module must have an input screen that allows the planner to identify the location and types of structures of interest in terms of the ASAN categories specified in Table 6-1. Using the relationships defined in Section 6.2.1,

ASAN must develop best estimates and variances of the inventory of vulnerable elements and their locations.

To facilitate the presentation of this processing it is useful to define some notational conventions. The following subscript notations will be used in the discussion:

Variables	Meaning
N	Number of Structural Elements
L	Number of Occurrences of a Load Condition
D	Damage Level -- Number of Elements Damaged
P	Probability of Damage

Subscripts

i	Standard Structural Planning Category, e.g., Residential, Schools, etc. (See Table 6-1)
j	Structural Element for Damage Reporting -- Windows, Plaster Ceilings, Plaster Walls and Bric-A-Brac
k	Primary Subclass of Structural Elements for Analysis -- Window Classes A - E, Plaster Wall Classes B - D
l	Structural Element Condition (Good or Damaged)
m	Location
n	Overpressure Interval
p	Load Duration Interval
q	Sonic Boom Wave Type (N-wave or Focused wave)

In terms of this rotation the input to the processing consists of an inventory of the exposed structural elements -- $N_{i,j,k,l,m}$ -- and an estimate of the frequency of occurrence of each loading condition -- $L_{m,n,p,q}$. The structural element inventory is expressed in terms of a best estimate, $E(N_{i,j,k,l,m})$, and a variance, $Var(N_{i,j,k,l,m})$. Associated with each combination of structural element type and loading condition are a mean and a variance of the estimate of the probability of damage -- $P_{j,k,l,n,p,q}$. Estimates of the mean and mean plus one sigma values of the damage probabilities ($P_{j,k,l,n,p,q}$) are found in Appendix A. The variances of these probabilities may be computed by squaring the difference between the mean plus one sigma values and the mean values.

The ASAN code must first identify the combinations of loading conditions and exposed structural elements which exist. For each of these conditions means and variances of anticipated damage levels are calculated using the following two equations.

(6-2)

$$E(D_{i,j,k,l,m,n,p,q}) = L_{m,n,p,q} \times E(N_{i,j,k,l,m}) \times E(P_{j,k,l,n,p,q})$$

$$Var(D_{i,j,k,l,m,n,p,q}) = L_{m,n,p,q} \times \{ E(N_{i,j,k,l,m}) \times Var(P_{j,k,l,n,p,q}) + Var(N_{i,j,k,l,m}) \times E(P_{j,k,l,n,p,q}) \}$$

Damage statistics for a structural planning category are obtained by summing over the analytical structural classes, structural element conditions, locations, and loading conditions as follows.

(6-3)

$$E(D_{i,j}) = \Sigma_{k,l,m,n,p,q} \quad E(D_{i,j,k,l,m,n,p,q})$$
$$Var(D_{i,j}) = \Sigma_{k,l,m,n,p,q} \quad Var(D_{i,j,k,l,m,n,p,q})$$

Total damage statistics are obtained by the further summation over planning categories as follows:

$$E(D_j) = \Sigma_i \; E(D_{i,j})$$
$$Var(D_j) = \Sigma_i \; Var(D_{i,j}) \qquad (6-4)$$

6.4 Damage Assessment Details

The ASAN conventional structures damage assessment module follows the basic form for calculating the probability of damage developed by Hershey and Higgins. The model develops damage probabilities by assessing the likelihood that the applied load exceeds the capacity of a structural element. We assume that the variations of loads consist of a systematic component and a random component. The result is a stress (which is a random variable with an associated uncertainty) applied to a structural element. The breaking strength of the structural element is, similarly, regarded to be a random variable. An effective factor of safety is defined by

Factor of Safety = (Breaking Strength)/(Applied Stress) (6-5)

To simplify the analysis, logarithms are taken of both sides giving

Log(FS) = Log(Strength) - Log(Stress) (6-6)

Following Hershey and Higgins, both terms on the right side of the equation are assumed to have probability distributions which are normal; thus, Log(Factor of Safety) is normally distributed and the Factor of Safety is lognormally distributed. Constitutive relationships for strength and stress are used to build up the probability distributions.

The model's constitutive relationship for the maximum stress is

$$\sigma_m = P_o \, (P_f/P_o) \, (P_e/P_f) \, (\sigma_d/P_e) \, (\sigma_m/\sigma_d) \qquad (6\text{-}7)$$

or

$$\sigma_m = P_o \, (P_f/P_o) \, (P_e/P_f) \, (F) \, (DAF)$$

The constitutive relationship for strength is

$$\sigma_G = F \, P_G \qquad (6\text{-}8)$$

where P_o = nominal (peak) overpressure <u>including modeled reflection factor</u>

P_f = actual ground level (peak) overpressure <u>including reflection factor</u>

P_e = peak external pressure applied to a particular structural element, includes orientation effects

σ_d = static stress = $(P_e \, a^2 b^2)/(2h^2 \, (a^2 + b^2))$

a,b,h = plate length, width and thickness

σ_m/σ_d = dynamic amplification factor, DAF

$F = (\sigma_d/P_e)$ = geometry/materials factor

The appearances of the geometry factor in both the stress and strength relationships directly offset each other. A discussion of breaking pressures, P_G, was presented earlier in the treatment of structural elements of concern. The next set of subsections addresses the factors in the load model.

The ASAN model treats two types of variational statistics. The first of these variational statistics are the <u>random</u> factors which result in the probability distribution for the load and strength; the second are the <u>systematic</u> factors which result in

uncertainty in this probability distribution. Table 6-24 summarizes the treatment of the two types of variability.

Table 6-24 Summary of ASAN Model Treatment of Variables

Variable	Random Component	Systematic Component (uncertainty)
$\log(P_o)$ P_o	---	Uncertainty due to intervals
$\log(P_f/P_o)$	Statistics depend on wave type (N-waves and focus)	---
$\log(P_e/P_f)$	---	From baseline model -- aircraft heading unknown
$\log(F)$	DETERMINISTIC	---
$\log(DAF)$	Statistics depend on wave type & duration, material & category.	
	Variance due to wave shape and damping variations	Uncertainty due to duration intervals and ranges of natural frequencies
$\log(P_G)$	Glass statistics depend on load duration & category other materials depend only on category	Uncertainty due to variation among members of category

6.4.1 Load Model

The first factor in this relationship, the predicted overpressure, is to be treated as deterministic for the purpose of assessing the **probability of damage** but variable for the purpose of assessing the **uncertainty** in this probability. The

variability arises from the manner in which this model must be integrated into ASAN. Peak overpressure intervals and the associated uncertainties are shown in Table 6-23 in Section 6-3.

The second factor in Equation 6-7 is the ratio of the actual ground level overpressure to the predicted overpressure. Determination of appropriate statistics for this factor depends on whether the sonic boom waveform is a (modified) N-wave or a focused wave and whether the location of interest is within the main portion of the sonic boom carpet (up to 80% of the distance from the flight track to lateral cutoff) or within the carpet fringes near cutoff.

The statistics provided by Hershey and Higgins are appropriate for the portion of the sonic boom carpet beginning at a distance of approximately 80% of the distance to lateral cutoff. However, for current U.S. Air Force supersonic operations the overpressures along the fringes of the sonic boom carpet are very low (lacking a focus). To simplify calculations these low overpressures will be treated in the same manner as those within the main carpet. Within the main carpet the NASA statistics (5) are more appropriate.

Although it is generally accepted that there is a greater uncertainty in predicting focus overpressures than overpressures for N-waves, no published statistics for the relationship between predictions and actual levels have been identified. A major source of the variation of the measured from predicted focused waves is the sensitivity of conditions for focusing to minor variations in aircraft maneuvers or to atmospheric anomalies. Similar factors are involved in the sonic propagation near the margins of the sonic boom carpet. Variations in these parameters may shift the location of a focus without significantly altering the maximum overpressure associated with the focus, or alter the local geometry of

focusing and cause significant overpressure and signature variations. We recommend that focus locations be spread probabilistically by the modeling module to account for the uncertainty in focus locations. Since peak overpressures associated with a focus decrease rapidly with distance from a focus, this can lead to large discrepancies between predicted pressures at a specific location and measured pressures for that location for a focus. Lacking appropriate statistics for the focus prediction uncertainty, the statistics developed by Hershey and Higgins have been adopted for this factor. Table 6-25 shows the provisional model values for the statistics of Hershey and Higgins.

Table 6-25 ASAN Model Statistics of P_f/P_o

Condition $\text{Log}(P_f/P_o)$	Mean $\text{Log}(P_f/P_o)$	Variance
Carpet boom	-0.0753	0.0040
Carpet fringes	-0.0753	0.0040
Focused boom	0.0471	0.0446

At a given overpressure, if N-waves and focused booms had the same uncertainty, less damage would be predicted for the focused boom. Focused booms induce a lesser dynamic response in structural elements. However, due to the very large uncertainty in the wave form and amplitude of focused booms included in the recommended statistics, the ASAN model predicts higher damage for focused booms. The dominant contribution is from the variability of the predicted free-field overpressure.

The third factor in the relationship for maximum stress is the ratio of peak external pressure applied to a particular structural element to the measured ground overpressure. If the geometry of the incoming wave and the surrounding structure were known for a particular element, the variability due to this factor would be expected to be very small. The unknown nature of this geometry contributes to the uncertainty in the damage estimates. Hershey and Higgins analyzed the White Sands data to develop statistics for this ratio based upon 484 ratio values. Because of the high degree of variability implied by their statistics, efforts were made to obtain source documents referenced by these investigators in an attempt to understand this scatter. The source documents retrieved account for only about 10% of the sample size reported to have been analyzed by Hershey and Higgins. Moreover, these documents did not provide any insights into the physical phenomena or instrumentation errors contributing to the large scatter they have reported. In the absence of a solid foundation for advancing alternative statistics, the baseline model values have been adopted for the damage uncertainty model for ASAN. These baseline values are shown in Table 6-26.

Table 6-26 ASAN $Log(P_e/P_f)$ Statistics

Element	$(Log(P_e/P_f))$	
	Mean	Variance
All elements except plaster ceilings	-0.1251	0.0439
Plaster ceilings	-0.1609	0.0029

The fourth factor is the geometry factor, which is deterministic. The fifth factor of the stress relationship, the Dynamic Amplification Factor, is discussed in Section 6.4.2.

6.4.2 Dynamic Amplification Factors

The DAF of the structural elements is dependent on the characteristics of the applied loading and the dynamic properties of the structural element. With respect to the loading, the factors affecting the DAF are the shape of the waveform and the duration. The dynamic properties of the structural element are described in terms of the natural frequency of vibration and a damping value. Variations in any of the previously mentioned factors will produce variations in the DAF. Variations due to damping and wave shape fall into the category of random effects and thus will contribute to the probability-of-damage model; in contrast, the variations in natural frequency and wave duration are systematic components which will enter the calculations of the uncertainty in damage estimates. Using an analytical approach, estimates were developed for variances characterizing each of these effects on the DAF and the resulting probability model and uncertainty model variances. Each of these factors is considered separately. Because of their length, the tables showing the various uncertainties have been excluded from this section and collected in Appendix B.

For the case of glass, the 2% damped DAF value is taken to represent the mean value. Since the maximum upper bound for the DAF value corresponds to the undamped case, the undamped DAF value is considered to be a 3 standard deviation upper bound. For the plaster elements, the 4% damped DAF value is taken to represent the mean and the 2% damped value is estimated to be one standard deviation above the mean.

Deviations of sonic booms from the idealized waveforms produce variations in the DAF. Analytical studies (7) were performed on the effects of variations in the shape of the N-wave. These studies presented an envelope DAF spectrum to represent the maximum DAF values for various properties of the waveform. The studies also considered asymmetry of the wave, rise time, spiked waves, and waves with shock reflections. The variance of the logarithm of the DAF is estimated by comparing the DAF value derived from the idealized N-wave with the corresponding DAF value from Crocker and Hudson's envelope. The envelope value is estimated to represent one standard deviation above the idealized value. Similar studies (see Section 3 of this report) have been employed to characterize the variation in DAF due to variability in the waveform of focused sonic booms.

Next, consider the systematic sources of variability of the DAF. First, consider the effect of the dynamic properties of the structural element. Recall that for each element category, an expected range of natural frequencies was presented. Referring to the DAF spectrum for the idealized sonic boom waveforms, for a given wave duration, the range of frequencies represents a band of values of the nondimensional frequency parameter on the abscissa of the graph. Using a nominal wave duration of 0.1 sec with the natural frequency range, maximum and minimum DAF values are evaluated in the range. The variance of the logarithm of the DAF due to the variation in the natural frequency is estimated from the difference between the maximum and minimum.

The second source of systematic variability of the DAF is the duration of the wave. Using the representative frequency for each element category and considering the designated wave duration intervals, maximum and minimum DAF values were determined. The variance of the logarithm of the DAF associated with wave duration is estimated from this range of DAF values by

considering the difference between the high to low values to represent four standard deviations.

6.5 Provisions for Extensions of the Model

Although the specific numerical values embodied in the ASAN damage calculation model are associated with particular types of structural elements and loads, the form of the model is much broader and more flexible. Should it be desirable to add additional elements or unconventional structures the following steps are required:

- Load Formulation: The load on an element must be describable in terms of a single parameter, an "effective applied peak overpressure." The "effective applied peak overpressure" must be simply (statistically) related to a predicted freefield load. (This load definition may depend upon spectral content of the load and its duration.)

- Response Model: A response model must be definable in terms of the applied load. The response must be approximated as a linear function of the "effective applied peak overpressure" for each class of loading waveform of interest. The response model must be capable of predicting the maximum dynamic structure response for the selected waveform.

- Capacity Model: A capacity model must be defined which is piecewise linear with respect to the "effective applied peak overpressure."

Whenever these three steps can be taken and the results expressed probabilistically, the model can be extended to that combination of load and structural element. In this regard,

when and if data become available to justify a cumulative damage model they can be integrated into the existing ASAN model by adding relations which express how the capacity statistics change with repeated loads.

7. CONCLUSIONS AND RECOMMENDATIONS

This chapter presents a summary of the findings of this study and also presents recommendations for further research. A literature review was conducted to identify existing sonic boom damage models. A model developed by Hershey and Higgins (2) was selected to serve as a baseline model to predict sonic boom damage to conventional structures. This model was reviewed and sensitivity analyses were conducted. As a result, the model was significantly enhanced. A literature review was also conducted to identify sonic boom cumulative damage models. Using candidate models, the relative significance of the cumulative damage effect was investigated by comparing the damage predictions for single event sonic booms and repeated sonic booms. Section 7.1 presents the conclusions and section 7.2 presents the recommendations for further study.

7.1 Conclusions

A comprehensive method for predicting damage to conventional structures due to single exposure sonic booms has been presented. The method is based upon the prediction of damage to specific building elements: windows, plaster ceilings and walls, and bric-a-brac. As a means of describing the exposed population of these elements, element categories have been defined. For windows, the categories are defined in terms of their surface areas. For the plaster elements, one ceiling model and three wall models are defined. The categories are selected to be representative of the existing windows and plaster elements in typical planning areas. For the windows and plaster elements, two states of condition are considered: those in good condition and those in a predamaged condition. The predamaged elements are modeled with reduced capacities. The predamaged elements are included in the damage prediction model by considering them to represent a specified small percentage of

the overall population of the windows and plaster elements. Also included is a building element exposure model. In the exposure model, mean and variance estimates are provided for the number of elements of each element category expected in each of the ASAN structure categories. The structure categories include: mobile homes, single family dwellings, multi-family dwellings, churches, hospitals, office buildings, commercial establishments, and schools. The exposure model provides estimates of the numbers of windows, plaster ceilings and walls, and bric-a-brac items for each of these structure types.

The damage prediction model for the building elements is derived from the baseline model developed by Hershey and Higgins (2). As a result of the critical review and sensitivity studies of this model, several improvements have been made. These improvements include:

1. Sources of variability of model parameters are categorized into components of <u>randomness</u> and components of <u>uncertainty</u>. Components of randomness enter the probabilistic damage assessments; components of uncertainty affect the uncertainty of damage estimates. This categorization allows the damage estimations to be made at a user-specified level of conservatism.

2. DAF statistics have been derived, for the first time, for focused sonic booms. The typical focused DAF is less than the typical DAF for an N-wave. The damage expected for a focused sonic boom at a given overpressure and specified wave duration would be less than that for an N-wave with the same overpressure and duration, given the same uncertainty in predicting the overpressure for both wave types. However, because there is much greater uncertainty in predicting the

focused boom overpressures, higher damage predictions are produced for focused booms.

3. Statistics for the load have been refined.

4. Improved response models have been employed in the analysis. These improved models result in more appropriate DAF and capacity statistics.

In using the recommended model to make damage predictions, it was found that the dominant contributors to the estimated number of damaged building elements are the preweakened elements. This also was a characteristic of the damage prediction for windows in the baseline model. Recall that the preweakened elements are modeled with reduced capacities. With these reduced capacities, the probability of damage for the respective elements is substantially increased. Although the preweakened elements are assumed to represent about 1% of the overall population, the increased probabilities of damage for the preweakened elements outweigh the damage contributions from the elements in good condition. For windows, the relative proportion of preweakened panes in the overall population is based on survey data taken during the Edwards AFB tests. This was adopted from the baseline model. The predamaged plaster elements are assumed to represent approximately the same fraction of the total population as the predamaged windows. Given that the preweakened elements are the dominant contributors to the estimated damage and that their relative numbers in the exposed population are based on a single survey, this is an area where further refinement can be made in the model. <u>The model can be improved with additional data to establish the relative numbers of the predamaged windows and plaster elements within the total exposed population</u>.

Furthermore, the capacity models for preweakened elements are based on only a limited amount of data. At the low overpressures typical of sonic booms, the capacity of the preweakened elements strongly affects the estimated damages. Thus, a better definition of the capacities of preweakened glass and plaster can significantly improve the model.

A review of the literature on cumulative damage from repeated sonic boom exposures was also conducted. In the literature, no conclusive evidence of a cumulative damage effect was shown. In addition, a study was performed to evaluate the relative significance of the cumulative damage effect with respect to the single event damage. Using fatigue models for glass and plaster that could be applied to the single event model, an illustrative comparison was made of the damage probabilities for single and repeated booms.

Several conclusions may be drawn from the cumulative damage literature review and a comparison of the damage probabilities for glass and plaster elements subjected to repeated sonic booms and single booms:

1. No model for predicting cumulative damage as a function of boom strength and the number of boom exposures are completely satisfactory.

2. The evidence for a cumulative damage effect in glass and plaster is weak. The test results show no substantial affect upon the glass itself by repeated booms. For plaster, the test results indicate a possible cumulative damage effect at higher overpressures.

3. There is evidence for a cumulative damage threshold overpressure. That is, if a cumulative damage effect

exists, it is associated with some minimum nominal overpressure.

4. The influences of naturally occurring forces due to the environment or from human activity, over time, can cause damage which is on the same order as that due to sonic booms.

5. The fatigue behavior of glass and plaster is poorly understood. In general, brittle materials, like glass and plaster, would not be expected to possess fatigue behavior similar to metallic materials. The sonic boom fatigue testing has concentrated on determining the behavior of the material by itself. However, there is evidence that the damage from repeated booms may be induced by stress raisers where the glass or plaster is supported. In windows, these stress raisers can be nails holding the window molding together, glazing points, or any other object which may abrade or impact the glass. For plaster elements, nails often used to attach lath to the supporting structural members can act to concentrate local stresses in the plaster during the dynamic response. The stress raisers may initiate cracking. However, if there are existing cracks in the plaster, the additional damage from repeated booms generally will appear as crack extensions.

6. From the sonic boom fatigue tests on glass and plaster, the proposed fatigue relationships have substantial uncertainty. First, there is a very limited amount of data. Second, there is substantial scatter in the existing test results.

Key findings from the investigation using the glass and plaster fatigue models, to compare the damage probabilities for repeated and single booms, are:

1. Using an estimate of 200 sonic boom exposures per year and a 50-year expected lifetime of a building, conservative estimates of the reduction in material capacity for a lifetime exposure to sonic booms were on the order of 20 to 25%.

2. If those fatigue relations are assumed to be valid, then the damage estimations for the lifetime exposure are within a one standard deviation uncertainty of the single event damage predictions.

3. Sound, defensible, cumulative damage models for glass and plaster cannot be recommended without further investigation.

Clearly the current state of the knowledge regarding cumulative damage from sonic booms is limited. The prediction of damage as a function of boom strength and the number of boom exposures cannot be made without great uncertainty. Moreover, the cumulative damage from the sonic booms is difficult to separate from the contribution to the damage from environmental factors.

7.2 Recommendations

The following discussion identifies additional investigations that should fill the most important technological gaps in knowledge about the effect of supersonic operations on conventional structures. All of these additional studies pertain to cumulative damage effects from repeated sonic booms.

As just stated, a cumulative damage model could not be recommended for ASAN because the data and models available in the literature are inadequate or do not conclusively show a cumulative damage effect. Repeated sonic boom tests on plaster wall panels and windows are recommended to investigate the cumulative damage effect. Two analytical studies are also recommended. One analytical study would evaluate the damage from environmental factors and relate it to sonic boom overpressures. The other analytical study would develop a cumulative damage model for bric-a-brac.

1. Repeated Boom Tests on Plaster Wall Panels

A test program evaluating the effect of repeated sonic boom loading on plaster wall panels is recommended. The objective is to evaluate a fatigue relation for the plaster wall. Previous fatigue testing did not use a complete wall panel--only the plaster itself. The test specimens should be full-scale wall panels with lath, plaster, wood studs, and the exterior finish. Furthermore, because there is evidence that plaster cracking may be initiated by stress raisers, testing of full-scale panels would help to confirm or refute this damage mechanism.

The basic test approach would be to repeatedly subject the test specimen to simulated N-waves of a given overpressure until cracking occurs. Each specimen would be cycled at only one overpressure level. The data would be compiled to develop a fatigue curve.

Program Plan

A. Design and Fabrication of the Test Apparatus -- This phase includes the development, design, and fabrication of a test chamber which would repeatedly apply

simulated N-wave loadings on the test specimens. The preliminary concept for the apparatus is a chamber that would control the pressures applied to the interior and exterior faces of the specimen to obtain a net effective pressure acting on the specimen which would simulate the N-wave.

B. Fabricate Test Specimens -- The test specimens shall be 8 ft x 8 ft (2.44 m x 2.44 m) standard wood frame construction wall panels, consisting of 2 in. x 4 in. (5.08 cm x 10.16 cm) wood studs, lath and plaster on the interior and stucco or wood siding on the exterior.

C. Plaster Coupon Tests -- Small plaster beam coupons will be taken from the plaster batches used to make the test specimens. The coupons will be tested to determine the tensile strength of the plaster used in the wall panels.

D. Wall Panel Static Load Tests -- The purpose of these tests is to establish the static pressure at which cracking occurs in the plaster. The strain data obtained in the coupon tests will be used to make a preliminary estimate of the expected breaking pressure. Cracking in the plaster will be detected using a thin, brittle, lacquer coating on the plaster. The coating can be selected to crack at about the same strain level associated with the expected breaking pressure of the plaster. Another approach for detecting cracking is to use small microphones and detect cracks by their acoustic emissions. The static failure load obtained in these tests will be used as a reference point to set the overpressure levels for the repeated boom testing.

E. <u>Repeated Sonic Boom Tests</u> -- The purpose of these tests is to generate the data necessary to develop a fatigue relationship for the plaster wall panel. In each test, the specimen will be subjected to repeated N-waves, at a single overpressure level, until cracking starts. The overpressure and the number of load cycles will be recorded. At minimum, tests at four overpressure levels will be required to develop a fatigue curve. Loading will be applied for up to 10,000 cycles.

F. <u>Data Analysis</u> -- The crack patterns in the plaster from the static and repeated boom tests will be reviewed to evaluate the failure modes and the effect of stress raisers in initiating the cracking. The data from the repeated boom test will be compiled to develop a fatigue relation for the plaster wall panel.

2. Alternate Test Plan for the Plaster Walls

Since the ultimate goal of the testing is to investigate cumulative damage effects in the plaster, an alternate approach would be to evaluate the influence of a low level overpressure load history on the wall panel. Rather than trying to develop a fatigue relation for the plaster, the tests will be aimed at evaluating the capacity of the wall after it has been subjected to a repeated boom load history. Here, the repeated booms will be applied at low overpressures typical of USAF supersonic operations (about 2 to 5 psf).

The test plan will follow steps A to D as previously listed. In Step E of the repeated boom tests, the specimen will be subjected to simulated sonic booms at a low overpressure level for a specific number of cycles. For example, one specimen may be subjected to 5,000 booms at 2 psf. Another

specimen may be subjected to 10,000 booms at 5 psf. At these low overpressure levels, damage would not be expected. After subjecting the specimen to the repeated booms, a static test would then be conducted to determine the failure pressure for the panel. This static failure pressure would be compared with the static failure pressures for the "new" specimens to evaluate the significance of the load history on the capacity of the panel.

An advantage of this approach is that the specimens will not need to be inspected while being subjected to the repeated sonic booms.

3. Repeated Sonic Boom Tests on Glass Panes

A test program is recommended to address the influence of stress raisers and support conditions on the capacity of glass panes subjected to repeated sonic booms. Two different mounting conditions should be considered: (1) the glass pane is mounted in a wood molding representative of existing construction, and (2) the glass pane is held in a fixture which provides clamped boundary conditions. The objective of the testing is to determine the relative influence of the support conditions on the capacity of the pane. The benefits of the test program are improved capacity models for the windows and improved correlation of the capacity model with observed phenomena. From the previous overflight tests and from damage claims, glass pane breakage generally starts near the edges of the pane, suggesting that the window supports may be strong contributors to the damage.

Program Plan

A. <u>Test Specimens</u> -- Type B windows are the most common in the ASAN structure categories and are therefore desirable for the testing. Two mounting conditions should be used: (1) a conventional wood frame molding, and (2) clamped boundary conditions typically used by glass manufacturers in their testing.

B. <u>Static Load Tests</u> -- Glass panes mounted in both support conditions are to be tested by incrementally applying static pressure. These tests are performed to obtain static capacities of the panes for each support condition. The static load capacities will provide a benchmark to set the overpressure levels for the repeated boom tests. Also, by comparing the capacities for the two support conditions, a relative measure of the influence of the support conditions can be evaluated.

C. <u>Repeated Boom Tests</u> -- The glass panes will be subjected to repeated sonic booms at selected overpressure levels for a maximum of 10,000 load cycles. The overpressures should be at low levels (e.g., 2-10 psf) typical of Air Force supersonic operations. The goal is to produce a load history in the panes that is representative of what may be expected in an Air Force planning area. At these low overpressures, damage would not be expected. After exposing the panes to the repeated boom history, a static pressure test will be performed to determine the failure pressure of a glass pane which has been exposed to repeated loading.

D. Data Analysis -- The static failure pressures for the glass panes with the repeated boom histories will be compared to the static failure pressures of the "new" glass panes to evaluate the strength reduction (if any) with the load history. The magnitude of the repeated boom overpressures can be used to quantify a cumulative damage threshold for those panes which show a loss of strength with the load history.

4. An analytical research program is recommended to investigate the cumulative damage effects from environmental factors. Previous damage surveys from the overflight tests found that the damage caused by the sonic booms was difficult to distinguish from the damage caused by environmental influences. The objective of the recommended study is to quantify the damage from natural phenomena and relate it to damage levels associated with exposure to a sonic boom at a specific overpressure. Existing data from the White Sands tests and data from underground blast tests conducted by the Bureau of Mines will be used. Plaster element crack measurements were made during both the boom periods and the quiet periods. The approach will be to use the observed damage over time for the quiet, ambient conditions and relate it to damage from exposure to a sonic boom overpressure through statistical analysis.

   The benefit of this program is that, if successful, it will provide a benchmark for the expected damage from the environmental factors. It should also relate the environmental damage in terms of a quantity which can be compared to sonic boom effects.

5. An analytical research program is recommended to develop a cumulative damage model for bric-a-brac. The objective of the study is to develop a method for estimating the number

of sonic boom exposures necessary to damage the bric-a-brac. Noting that some bric-a-brac items can "walk" in response to the sonic boom, a concept for modeling the bric-a-brac response is to use a random walk model. Also, methods from seismic intensity studies may be used to correlate the "walking" of the bric-a-brac items to the intensity of the input vibration.

The benefit of this study is that an additional bric-a-brac damage model can be developed. The bric-a-brac model for single exposure events is empirically derived from very few data. The study will investigate a different method for modeling bric-a-brac damage and provide additional statistics to the empirical models.

Table 7-1 presents an overview of the recommended programs. The potential benefits and risks for each program are briefly listed. In addition, each program is rated for its relative importance (1 being highest) and a rough, order-of-magnitude cost estimate is provided.

Table 7-1 Recommended Programs for Further Study

Program	Benefits	Risks	Importance	ROM Cost
Test apparatus	Required test chamber to conduct the repeated boom tests	Inaccurate simulation of N-wave	1	$50,000
Repeated boom tests on plaster wall panels	Improved capacity model for fatigue behavior, investigate crack initiation by stress raisers, realistic configuration of the test sample	Potential scatter in data or too few data points may produce inconclusive results	1	$100,000
Repeated boom tests on window panes	Improved glass capacity model, correlation of capacity to mounting conditions on cumulative damage effect	Scatter in glass strength may greatly outweigh the influence of the support conditions and the cumulative damage effect	2	$100,000
Cumulative damage from environmental effects	Provide benchmark damage level expected from environmental factors over time	Data may be insufficient, uncertainty in the result may be very high	2	$25,000-$30,000
Bric-a-brac cumulative damage model	Develop new model for bric-a-brac based on random walk model, predict number of exposures required for breakage (seismic data for bric-a-brac damage intensities)	Model may not correlate well with observed behavior, there may be insufficient test data to verify model	3	$25,000-$30,000

REFERENCES

1. Hershey, R.L. and Higgins, T.H., "Statistical Prediction Model for Glass Breakage From Nominal Sonic Boom Loads," FAA Report No. FAA-RD-73-79, January 1973.

2. Hershey, R.L. and Higgins, T.H., "Statistical Model of Sonic Boom Structural Damage," FAA Report No. FAA-RD-76-87, May 1976.

3. Anonymous, "Assessing Noise Impacts of Air Force Operations -- Guidelines," USAF.

4. Blume, J.A., Sharpe, R.L., Kost, G. and Proulx, J., "Response of Structures to Sonic Booms Produced by XB-70, B-58, and F-104 Aircraft Based on Sonic Boom Experiments at Edwards Air Force Base," NSBEO-2-67, October, 1967.

5. Maglierri, D., Huckel, V., and Henderson, H., "Variability in Sonic Boom Signatures Measured Along An 8,000 Foot Linear Array," NASA TN D-5040, February, 1969.

6. Wiggins, J.H., Effects of Sonic Boom, J H Wiggins Co., Palos Verdes Estates, California, 1969.

7. Crocker, M.J. and Hudson, R.R., "Structural Response To Sonic Booms," Journal of Sound and Vibration, Volume 9, Number 3, 1969.

8. Taylor, C., "Window Survey Update," NTS Engineering Report 86-3145-06, September, 1986.

9. Hershey, R.L., Kevala, R.J., and Burns, S., "Analysis of the Effects of Concorde Aircraft Noise on Historic Structures," FAA Report No. FAA-RD-775-118, July, 1975.

10. Abiassi, J.J., "The Strength of Weathered Window Glass Using Surface Characteristics," Institute For Disaster Research, Texas Tech University, Lubbock, TX, June 1981.

11. Norville, H.S. and Minor, J.E., "Strength of Weathered Window Glass," American Ceramic Society Bulletin, Vol 64, No. 11, November, 1985.

12. Pape, E.J., Minor, J.E. and De Hart, R.C., "Evaluation of Window Pane Damage Intensity in San Antonio Resulting from Medina Facility Explosion on 13 November 1963," Southwest Research Institute, San Antonio, TX, January 1966.

13. Wiggins, J.H., "The Effects of Sonic Boom on Structural Behavior - A Supplementary Analysis Report," SST Report No. 65-18, John Blume and Associates, San Francisco, California, October, 1965.

14. Wiggins, J.H., "Effect of Sonic Boom on Structural Behavior," Materials Research and Standards, ASTM, Vol. 7., No. 6, pp. 235-245, June, 1967.

15. Wiggins, J.H., Sonic Boom and Natural Deterioration Effects on Buildings: White Sands N.M. Structure Resurvey, Report No. FAA-RD-72-25, J H Wiggins Co., Palos Verdes Estates, California, February, 1972.

16. Webb, D.R.B., Effects of Sonic Booms on Buildings in Relation to Environmental Effects, Technical Report No. 78118, Royal Aircraft Establishment, October, 1978.

17. Stagg, M.S., Siskind, D.E., Stevens, M.G., and Dowding, C.H., Effects of Repeated Blasting on a Wood Frame House, Bureau of Mines Report of Investigations, RI8896, 1984.

18. Wiggins, J.H., Commentary On Cumulative Damage From Repeated Sonic Booms, Crisis Management Corporation, Redondo Beach, California, April, 1988.

19. Kao, G., An Experimental Study to Determine the Effects of Repetitive Sonic Booms On Glass Breakage, Report No. FAA-NO-70, Wyle Laboratories, Huntsville, Alabama, June, 1970.

20. White, R.W., Effects of Repetitive Sonic Booms on Glass Breakage, Report No. FAA-RD-72-43, Wyle Laboratories, Huntsville, Alabama, April, 1972.

21. Pallant, R.J., The Response of Some Leaded Windows to Simulated Sonic Bangs, Technical Report No. 73111, Royal Aircraft Establishment, Farnborough, England, November, 1973.

22. Leigh, B.R., Lifetime Concept of Plaster Panels Subjected to Sonic Boom, UTIAS Technical Note No. 191, Institute for Aerospace Studies, University of Toronto, Canada, July, 1974.

23. Peschke, W., Sanlorenzo, E., and Abele, M., Experimental Determination of Acoustic and Structural Behavior of Wall Panel - Cavity Configurations Exposed to Sonic Booms, Report No. NASA CR-111925, General Applied Science Laboratories, Inc., Westbury, New York, 1971

24. Galloway, W.J., personal communication, June, 1988.

25. Pretlove, A.J. and Bowler, J.F., " An Estimate of Sonic Boom Damage To Large Windows," Journal of Sound and Vibration, Vol. 22, No. 5, pp 107-112, 1972.

26. Seaman, L., "Response of Windows To Sonic Booms," Stanford Research Institute Interim Technical Report No. 7, 1967.

APPENDIX A

SONIC BOOM DAMAGE MATRICES

This appendix contains tables which show the probability of damage for a range of peak overpressure amplitudes, wave durations, focused waves and N-waves: a) to windows in each of the five window size categories for both of the window conditions, b) to plaster walls and ceilings in four categories and two conditions, and c) to bric-a-brac. Two tables are presented for each combination of structural element and loading condition. The first table shows the mean estimate of the probability of damage; the second shows the mean plus one standard deviation estimate of the probability of damage.

Table A-1a

Mean Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = A

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2.5 - 4.0	.0000E+00	.0000E+00	.0000E+00	.0000E+00
4.0 - 6.0	.0000E+00	.0000E+00	.0000E+00	.0000E+00
6.0 - 8.0	.0000E+00	.0000E+00	.0000E+00	.0000E+00
8.0 - 10.0	.0000E+00	.0000E+00	.0000E+00	.0000E+00
10.0 - 12.	.0000E+00	.0000E+00	.0000E+00	.0000E+00
12.0 - 15.	.0000E+00	.0000E+00	.0000E+00	.1110E-15
15.0 - 18.	.2220E-15	.7772E-15	.1887E-14	.4330E-14
18.0 - 21.	.5662E-14	.1954E-13	.4674E-13	.1019E-12
21.0 - 24.	.8371E-13	.2749E-12	.6316E-12	.1328E-11
24.0 - 27.	.8006E-12	.2506E-11	.5562E-11	.1133E-10
27.0 - 30.	.5471E-11	.1641E-10	.3534E-10	.7004E-10

Table A-1b

Mean Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = B

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN +.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2.5 - 4.0	.0000E+00	.0000E+00	.0000E+00	.0000E+00
4.0 - 6.0	.0000E+00	.0000E+00	.0000E+00	.0000E+00
6.0 - 8.0	.0000E+00	.0000E+00	.0000E+00	.0000E+00
8.0 - 10.0	.0000E+00	.0000E+00	.1110E-15	.3331E-15
10.0 - 12.	.5551E-15	.2554E-14	.7438E-14	.1810E-13
12.0 - 15.	.2398E-13	.1091E-12	.2958E-12	.6772E-12
15.0 - 18.	.8687E-12	.3591E-11	.9130E-11	.1981E-10
18.0 - 21.	.1441E-10	.5506E-10	.1328E-09	.2754E-09
21.0 - 24.	.1406E-09	.5023E-09	.1158E-08	.2312E-08
24.0 - 27.	.9369E-09	.3156E-08	.6991E-08	.1350E-07
27.0 - 30.	.4666E-08	.1492E-07	.3193E-07	.5988E-07

Table A-1c

Mean Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = C

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2.5 - 4.0	.4774E-14	.1121E-13	.1876E-13	.7927E-13
4.0 - 6.0	.6121E-11	.1301E-10	.2043E-10	.7214E-10
6.0 - 8.0	.9159E-09	.1793E-08	.2679E-08	.8210E-08
8.0 - 10.0	.2522E-07	.4648E-07	.6698E-07	.1851E-06
10.0 - 12.	.2837E-06	.4986E-06	.6980E-06	.1777E-05
12.0 - 15.	.2646E-05	.4435E-05	.6032E-05	.1415E-04
15.0 - 18.	.2013E-04	.3218E-04	.4254E-04	.9203E-04
18.0 - 21.	.9402E-04	.1446E-03	.1868E-03	.3780E-03
21.0 - 24.	.3170E-03	.4718E-03	.5972E-03	.1142E-02
24.0 - 27.	.8482E-03	.1227E-02	.1526E-02	.2780E-02
27.0 - 30.	.1909E-02	.2693E-02	.3300E-02	.5757E-02

Table A-1d

Mean Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = D

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec)			
	0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.2154E-13	.1210E-13	.1055E-13
2.5 - 4.0	.3038E-11	.3342E-07	.2200E-07	.1985E-07
4.0 - 6.0	.1202E-08	.3571E-05	.2510E-05	.2302E-05
6.0 - 8.0	.7655E-07	.8155E-04	.6034E-04	.5602E-04
8.0 - 10.0	.1177E-05	.5939E-03	.4561E-03	.4273E-03
10.0 - 12.	.8553E-05	.2394E-02	.1893E-02	.1786E-02
12.0 - 15.	.5274E-04	.8223E-02	.6691E-02	.6359E-02
15.0 - 18.	.2724E-03	.2391E-01	.2001E-01	.1915E-01
18.0 - 21.	.9396E-03	.5157E-01	.4415E-01	.4248E-01
21.0 - 24.	.2477E-02	.9157E-01	.7991E-01	.7725E-01
24.0 - 27.	.5403E-02	.1423E+00	.1262E+00	.1225E+00
27.0 - 30.	.1023E-01	.2008E+00	.1805E+00	.1758E+00

Table A-1e

Mean Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = E

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.1642E-10	.4006E-08	.1971E-08
2.5 - 4.0	.4304E-10	.1343E-05	.6452E-04	.3961E-04
4.0 - 6.0	.7172E-08	.5374E-04	.1316E-02	.8853E-03
6.0 - 8.0	.2570E-06	.6305E-03	.9152E-02	.6609E-02
8.0 - 10.0	.2751E-05	.2995E-02	.2985E-01	.2267E-01
10.0 - 12.	.1554E-04	.8919E-02	.6634E-01	.5239E-01
12.0 - 15.	.7687E-04	.2338E-01	.1307E+00	.1072E+00
15.0 - 18.	.3291E-03	.5371E-01	.2283E+00	.1941E+00
18.0 - 21.	.9948E-03	.9762E-01	.3336E+00	.2917E+00
21.0 - 24.	.2383E-02	.1525E+00	.4362E+00	.3901E+00
24.0 - 27.	.4839E-02	.2146E+00	.5298E+00	.4826E+00
27.0 - 30.	.8685E-02	.2802E+00	.6115E+00	.5654E+00

Table A-2a

Mean Plus One Sigma Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = A

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2.5 - 4.0	.0000E+00	.0000E+00	.0000E+00	.0000E+00
4.0 - 6.0	.0000E+00	.0000E+00	.0000E+00	.0000E+00
6.0 - 8.0	.0000E+00	.0000E+00	.0000E+00	.1110E-15
8.0 - 10.0	.5551E-15	.1998E-14	.4885E-14	.1099E-13
10.0 - 12.	.2676E-13	.9004E-13	.2104E-12	.4490E-12
12.0 - 15.	.1075E-11	.3340E-11	.7380E-11	.1497E-10
15.0 - 18.	.3238E-10	.9312E-10	.1948E-09	.3760E-09
18.0 - 21.	.4598E-09	.1240E-08	.2478E-08	.4591E-08
21.0 - 24.	.3916E-08	.1000E-07	.1922E-07	.3437E-07
24.0 - 27.	.2310E-07	.5625E-07	.1045E-06	.1812E-06
27.0 - 30.	.1031E-06	.2406E-06	.4337E-06	.7319E-06

Table A-2b

Mean Plus One Sigma Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = B

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2.5 - 4.0	.0000E+00	.0000E+00	.0000E+00	.0000E+00
4.0 - 6.0	.0000E+00	.1110E-15	.2220E-15	.6661E-15
6.0 - 8.0	.1221E-13	.5640E-13	.1548E-12	.3577E-12
8.0 - 10.0	.1104E-11	.4526E-11	.1146E-10	.2476E-10
10.0 - 12.	.3108E-10	.1159E-09	.2753E-09	.5639E-09
12.0 - 15.	.7205E-09	.2443E-08	.5442E-08	.1056E-07
15.0 - 18.	.1276E-07	.3940E-07	.8241E-07	.1516E-06
18.0 - 21.	.1176E-06	.3359E-06	.6668E-06	.1174E-05
21.0 - 24.	.6959E-06	.1861E-05	.3533E-05	.5992E-05
24.0 - 27.	.3002E-05	.7578E-05	.1384E-04	.2272E-04
27.0 - 30.	.1019E-04	.2446E-04	.4317E-04	.6884E-04

Table A-2c

Mean Plus One Sigma Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = C

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.1110E-15	.1110E-15	.6661E-15
2.5 - 4.0	.1635E-09	.3171E-09	.4801E-09	.1547E-08
4.0 - 6.0	.5111E-07	.8992E-07	.1280E-06	.3455E-06
6.0 - 8.0	.2486E-05	.4053E-05	.5499E-05	.1293E-04
8.0 - 10.0	.3073E-04	.4741E-04	.6210E-04	.1320E-03
10.0 - 12.	.1847E-03	.2727E-03	.3474E-03	.6820E-03
12.0 - 15.	.9352E-03	.1322E-02	.1638E-02	.2969E-02
15.0 - 18.	.3850E-02	.5214E-02	.6289E-02	.1055E-01
18.0 - 21.	.1088E-01	.1423E-01	.1679E-01	.2646E-01
21.0 - 24.	.2401E-01	.3050E-01	.3533E-01	.5281E-01
24.0 - 27.	.4460E-01	.5524E-01	.6298E-01	.9000E-01
27.0 - 30.	.7298E-01	.8846E-01	.9948E-01	.1367E+00

Table A-2d

Mean Plus One Sigma Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = D

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.5751E-13	.1070E-08	.6887E-09	.6030E-09
2.5 - 4.0	.2093E-07	.2521E-04	.1858E-04	.1689E-04
4.0 - 6.0	.2346E-05	.8190E-03	.6413E-03	.5940E-03
6.0 - 8.0	.5512E-04	.7384E-02	.6057E-02	.5692E-02
8.0 - 10.0	.4164E-03	.2788E-01	.2365E-01	.2245E-01
10.0 - 12.	.1736E-02	.6763E-01	.5886E-01	.5633E-01
12.0 - 15.	.6231E-02	.1423E+00	.1270E+00	.1225E+00
15.0 - 18.	.1874E-01	.2573E+00	.2350E+00	.2283E+00
18.0 - 21.	.4161E-01	.3807E+00	.3541E+00	.3460E+00
21.0 - 24.	.7577E-01	.4978E+00	.4696E+00	.4609E+00
24.0 - 27.	.1203E+00	.6008E+00	.5732E+00	.5646E+00
27.0 - 30.	.1730E+00	.6866E+00	.6611E+00	.6530E+00

Table A-2e

Mean Plus One Sigma Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW
CONDITION = HEALTHY
CATEGORY = E
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.6931E-09	.9076E-05	.3048E-03	.1964E-03
2.5 - 4.0	.1174E-04	.6960E-02	.5476E-01	.4291E-01
4.0 - 6.0	.3234E-03	.5035E-01	.2170E+00	.1840E+00
6.0 - 8.0	.2831E-02	.1594E+00	.4451E+00	.3991E+00
8.0 - 10.0	.1095E-01	.3007E+00	.6318E+00	.5867E+00
10.0 - 12.	.2785E-01	.4429E+00	.7628E+00	.7250E+00
12.0 - 15.	.6275E-01	.5939E+00	.8636E+00	.8362E+00
15.0 - 18.	.1242E+00	.7308E+00	.9298E+00	.9126E+00
18.0 - 21.	.2004E+00	.8237E+00	.9632E+00	.9526E+00
21.0 - 24.	.2840E+00	.8846E+00	.9802E+00	.9738E+00
24.0 - 27.	.3685E+00	.9242E+00	.9891E+00	.9852E+00
27.0 - 30.	.4492E+00	.9497E+00	.9938E+00	.9914E+00

Table A-3a

Mean Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = A

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2.5 - 4.0	.3075E-13	.5729E-13	.2587E-13	.1610E-13
4.0 - 6.0	.4103E-11	.7243E-11	.3498E-11	.2270E-11
6.0 - 8.0	.1436E-09	.2430E-09	.1239E-09	.8299E-10
8.0 - 10.0	.1644E-08	.2696E-08	.1430E-08	.9808E-09
10.0 - 12.	.1030E-07	.1649E-07	.9028E-08	.6307E-08
12.0 - 15.	.5914E-07	.9231E-07	.5217E-07	.3713E-07
15.0 - 18.	.3065E-06	.4669E-06	.2723E-06	.1974E-06
18.0 - 21.	.1122E-05	.1674E-05	.1002E-05	.7378E-06
21.0 - 24.	.3238E-05	.4749E-05	.2906E-05	.2167E-05
24.0 - 27.	.7871E-05	.1137E-04	.7095E-05	.5352E-05
27.0 - 30.	.1678E-04	.2392E-04	.1518E-04	.1157E-04

Table A-3b

Mean Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = B

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2.5 - 4.0	.1144E-11	.6174E-11	.7576E-11	.2996E-11
4.0 - 6.0	.1123E-09	.5177E-09	.6230E-09	.2690E-09
6.0 - 8.0	.3082E-08	.1255E-07	.1487E-07	.6879E-08
8.0 - 10.0	.2948E-07	.1096E-06	.1284E-06	.6248E-07
10.0 - 12.	.1601E-06	.5537E-06	.6431E-06	.3258E-06
12.0 - 15.	.7958E-06	.2561E-05	.2948E-05	.1554E-05
15.0 - 18.	.3574E-05	.1071E-04	.1222E-04	.6703E-05
18.0 - 21.	.1161E-04	.3279E-04	.3714E-04	.2106E-04
21.0 - 24.	.3016E-04	.8126E-04	.9148E-04	.5334E-04
24.0 - 27.	.6730E-04	.1730E-03	.1936E-03	.1157E-03
27.0 - 30.	.1326E-03	.3278E-03	.3653E-03	.2230E-03

Table A-3c

Mean Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = C

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1255E-12	.1783E-11	.5570E-11	.2597E-10
2.5 - 4.0	.4600E-08	.3729E-07	.9075E-07	.2993E-06
4.0 - 6.0	.1894E-06	.1213E-05	.2659E-05	.7588E-05
6.0 - 8.0	.2639E-05	.1405E-04	.2838E-04	.7229E-04
8.0 - 10.0	.1543E-04	.7179E-04	.1366E-03	.3204E-03
10.0 - 12.	.5686E-04	.2378E-03	.4316E-03	.9482E-03
12.0 - 15.	.1921E-03	.7225E-03	.1251E-02	.2576E-02
15.0 - 18.	.5902E-03	.1998E-02	.3304E-02	.6383E-02
18.0 - 21.	.1403E-02	.4356E-02	.6934E-02	.1271E-01
21.0 - 24.	.2804E-02	.8093E-02	.1247E-01	.2187E-01
24.0 - 27.	.4955E-02	.1342E-01	.2012E-01	.3396E-01
27.0 - 30.	.7979E-02	.2044E-01	.2990E-01	.4881E-01

Table A-3d

Mean Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = D

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.2234E-11	.2503E-09	.5644E-08	.4753E-07
2.5 - 4.0	.2031E-07	.8529E-06	.9488E-05	.4763E-04
4.0 - 6.0	.5254E-06	.1463E-04	.1211E-03	.4903E-03
6.0 - 8.0	.5343E-05	.1078E-03	.7085E-03	.2425E-02
8.0 - 10.0	.2552E-04	.4069E-03	.2262E-02	.6854E-02
10.0 - 12.	.8146E-04	.1078E-02	.5252E-02	.1446E-01
12.0 - 15.	.2421E-03	.2663E-02	.1137E-01	.2850E-01
15.0 - 18.	.6645E-03	.6091E-02	.2287E-01	.5224E-01
18.0 - 21.	.1455E-02	.1147E-01	.3875E-01	.8211E-01
21.0 - 24.	2734E-02	.1898E-01	.5864E-01	.1166E+00
24.0 - 27.	.4605E-02	.2863E-01	.8190E-01	.1543E+00
27.0 - 30.	.7139E-02	.4029E-01	.1078E+00	.1938E+00

Table A-3e

Mean Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = E

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.2603E-10	.1281E-08	.4362E-07	.4315E-06
2.5 - 4.0	.1415E-06	.2994E-05	.4412E-04	.2417E-03
4.0 - 6.0	.2959E-05	.4395E-04	.4570E-03	.1959E-02
6.0 - 8.0	.2548E-04	.2870E-03	.2273E-02	.8053E-02
8.0 - 10.0	.1078E-03	.9931E-03	.6456E-02	.1993E-01
10.0 - 12.	.3129E-03	.2458E-02	.1368E-01	.3792E-01
12.0 - 15.	.8460E-03	.5672E-02	.2706E-01	.6749E-01
15.0 - 18.	.2116E-02	.1214E-01	.4982E-01	.1121E+00
18.0 - 21.	.4290E-02	.2166E-01	.7860E-01	.1627E+00
21.0 - 24.	.7555E-02	.3422E-01	.1120E+00	.2163E+00
24.0 - 27.	.1203E-01	.4963E-01	.1486E+00	.2705E+00
27.0 - 30.	.1776E-01	.6748E-01	.1871E+00	.3236E+00

Table A-4a

Mean Plus One Sigma Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = A

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1443E-14	.2554E-14	.1110E-14	.6661E-15
2.5 - 4.0	.4880E-10	.7959E-10	.3957E-10	.2603E-10
4.0 - 6.0	.3225E-08	.5012E-08	.2669E-08	.1829E-08
6.0 - 8.0	.6423E-07	.9608E-07	.5400E-07	.3820E-07
8.0 - 10.0	.4931E-06	.7173E-06	.4194E-06	.3037E-06
10.0 - 12.	.2261E-05	.3217E-05	.1942E-05	.1433E-05
12.0 - 15.	.9603E-05	.1336E-04	.8325E-05	.6259E-05
15.0 - 18.	.3654E-04	.4976E-04	.3198E-04	.2449E-04
18.0 - 21.	.1037E-03	.1387E-03	.9149E-04	.7114E-04
21.0 - 24.	.2413E-03	.3178E-03	.2142E-03	.1687E-03
24.0 - 27.	.4864E-03	.6319E-03	.4342E-03	.3459E-03
27.0 - 30.	.8790E-03	.1129E-02	.7887E-03	.6347E-03

Table A-4b

Mean Plus One Sigma Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = B

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.4963E-13	.2762E-12	.3431E-12	.1277E-12
2.5 - 4.0	.9130E-09	.3646E-08	.4344E-08	.1949E-08
4.0 - 6.0	.4535E-07	.1561E-06	.1825E-06	.8928E-07
6.0 - 8.0	.7206E-06	.2208E-05	.2543E-05	.1332E-05
8.0 - 10.0	.4683E-05	.1318E-04	.1501E-04	.8260E-05
10.0 - 12.	.1880E-04	.4944E-04	.5583E-04	.3197E-04
12.0 - 15.	.6985E-04	.1716E-03	.1921E-03	.1145E-03
15.0 - 18.	.2328E-03	.5352E-03	.5939E-03	.3680E-03
18.0 - 21.	.5922E-03	.1288E-02	.1420E-02	.9084E-03
21.0 - 24.	.1254E-02	.2603E-02	.2851E-02	.1875E-02
24.0 - 27.	.2329E-02	.4643E-02	.5058E-02	.3407E-02
27.0 - 30.	.3916E-02	.7532E-02	.8169E-02	.5618E-02

Table A-4c

Mean Plus One Sigma Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = C

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1268E-08	.1052E-07	.2663E-07	.9359E-07
2.5 - 4.0	.3136E-05	.1577E-04	.3182E-04	.8159E-04
4.0 - 6.0	.5793E-04	.2328E-03	.4241E-03	.9425E-03
6.0 - 8.0	.4287E-03	.1448E-02	.2436E-02	.4846E-02
8.0 - 10.0	.1594E-02	.4741E-02	.7530E-02	.1383E-01
10.0 - 12.	.4118E-02	.1109E-01	.1683E-01	.2903E-01
12.0 - 15.	.9834E-02	.2398E-01	.3480E-01	.5641E-01
15.0 - 18.	.2136E-01	.4730E-01	.6573E-01	.1004E+00
18.0 - 21.	.3822E-01	.7826E-01	.1050E+00	.1527E+00
21.0 - 24.	.6013E-01	.1153E+00	.1502E+00	.2099E+00
24.0 - 27.	.8645E-01	.1567E+00	.1991E+00	.2689E+00
27.0 - 30.	.1162E+00	.2007E+00	.2495E+00	.3274E+00

Table A-4d

Mean Plus One Sigma Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = D

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.3721E-08	.1744E-06	.2202E-05	.1265E-04
2.5 - 4.0	.3758E-05	.7383E-04	.4974E-03	.1795E-02
4.0 - 6.0	.5319E-04	.7064E-03	.3583E-02	.1047E-01
6.0 - 8.0	.3353E-03	.3286E-02	.1339E-01	.3326E-01
8.0 - 10.0	.1140E-02	.8948E-02	.3110E-01	.6879E-01
10.0 - 12.	.2787E-02	.1838E-01	.5643E-01	.1140E+00
12.0 - 15.	.6392E-02	.3544E-01	.9624E-01	.1779E+00
15.0 - 18.	.1352E-01	.6332E-01	.1528E+00	.2596E+00
18.0 - 21.	.2391E-01	.9757E-01	.2140E+00	.3399E+00
21.0 - 24.	.3751E-01	.1363E+00	.2763E+00	.4153E+00
24.0 - 27.	.5407E-01	.1779E+00	.3372E+00	.4839E+00
27.0 - 30.	.7314E-01	.2208E+00	.3950E+00	.5452E+00

Table A-4e

Mean Plus One Sigma Estimates of Breakage Probabilities for Windows

MATERIAL TYPE = WINDOW

CONDITION = HEALTHY

CATEGORY = E

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.4680E-07	.1284E-05	.1849E-04	.1075E-03
2.5 - 4.0	.2804E-04	.3500E-03	.2435E-02	.8397E-02
4.0 - 6.0	.3055E-03	.2657E-02	.1344E-01	.3680E-01
6.0 - 8.0	.1574E-02	.1035E-01	.4097E-01	.9420E-01
8.0 - 10.0	.4616E-02	.2477E-01	.8227E-01	.1671E+00
10.0 - 12.	.1005E-01	.4600E-01	.1333E+00	.2461E+00
12.0 - 15.	.2053E-01	.8024E-01	.2034E+00	.3426E+00
15.0 - 18.	.3881E-01	.1303E+00	.2907E+00	.4494E+00
18.0 - 21.	.6262E-01	.1858E+00	.3746E+00	.5416E+00
21.0 - 24.	.9096E-01	.2434E+00	.4517E+00	.6190E+00
24.0 - 27.	.1227E+00	.3009E+00	.5207E+00	.6830E+00
27.0 - 30.	.1567E+00	.3563E+00	.5814E+00	.7355E+00

Table A-5a

Mean Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS

CONDITION = PREDAMAGED

CATEGORY = A

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.0000E+00	.0000E+00	.0000E+00
2.5 - 4.0	.3116E-10	.8980E-10	.1879E-09	.3630E-09
4.0 - 6.0	.2286E-07	.5573E-07	.1035E-06	.1796E-06
6.0 - 8.0	.1910E-05	.4084E-05	.6913E-05	.1102E-04
8.0 - 10.0	.3178E-04	.6179E-04	.9773E-04	.1465E-03
10.0 - 12.0	.2292E-03	.4133E-03	.6198E-03	.8855E-03
12.0 - 15.0	.1318E-02	.2206E-02	.3139E-02	.4276E-02
15.0 - 18.0	.5983E-02	.9313E-02	.1259E-01	.1637E-01
18.0 - 21.0	.1776E-01	.2606E-01	.3378E-01	.4231E-01
21.0 - 24.0	.3999E-01	.5585E-01	.6991E-01	.8488E-01
24.0 - 27.0	.7443E-01	.9968E-01	.1212E+00	.1433E+00
27.0 - 30.0	.1207E+00	.1559E+00	.1848E+00	.2137E+00

Table A-5b

Mean Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS

CONDITION = PREDAMAGED

CATEGORY = B

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.7772E-15	.3997E-14	.1132E-13	.2731E-13
2.5 - 4.0	.1981E-07	.6034E-07	.1249E-06	.2280E-06
4.0 - 6.0	.4390E-05	.1093E-04	.1975E-04	.3213E-04
6.0 - 8.0	.1487E-03	.3161E-03	.5141E-03	.7652E-03
8.0 - 10.0	.1309E-02	.2483E-02	.3742E-02	.5223E-02
10.0 - 12.0	.5784E-02	.1004E-01	.1426E-01	.1893E-01
12.0 - 15.0	.2071E-01	.3295E-01	.4415E-01	.5585E-01
15.0 - 18.0	.5985E-01	.8757E-01	.1110E+00	.1341E+00
18.0 - 21.0	.1242E+00	.1700E+00	.2063E+00	.2402E+00
21.0 - 24.0	.2088E+00	.2708E+00	.3172E+00	.3588E+00
24.0 - 27.0	.3050E+00	.3783E+00	.4305E+00	.4756E+00
27.0 - 30.0	.4036E+00	.4825E+00	.5362E+00	.5811E+00

Table A-5c

Mean Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS
CONDITION = PREDAMAGED
CATEGORY = C
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec)			
	0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.3670E-06	.6416E-06	.8953E-06	.2258E-05
2.5 - 4.0	.3888E-02	.5358E-02	.6473E-02	.1085E-01
4.0 - 6.0	.4524E-01	.5670E-01	.6470E-01	.9229E-01
6.0 - 8.0	.1769E+00	.2068E+00	.2263E+00	.2873E+00
8.0 - 10.0	.3576E+00	.3993E+00	.4253E+00	.5005E+00
10.0 - 12.0	.5331E+00	.5764E+00	.6023E+00	.6733E+00
12.0 - 15.0	.7027E+00	.7396E+00	.7607E+00	.8155E+00
15.0 - 18.0	.8362E+00	.8619E+00	.8761E+00	.9107E+00
18.0 - 21.0	.9116E+00	.9279E+00	.9366E+00	.9570E+00
21.0 - 24.0	.9524E+00	.9623E+00	.9675E+00	.9791E+00
24.0 - 27.0	.9742E+00	.9801E+00	.9831E+00	.9896E+00
27.0 - 30.0	.9858E+00	.9893E+00	.9911E+00	.9947E+00

Table A-5d

Mean Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS
CONDITION = PREDAMAGED
CATEGORY = D
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1055E-04	.2768E-02	.2195E-02	.2073E-02
2.5 - 4.0	.1784E-01	.2671E+00	.2431E+00	.2375E+00
4.0 - 6.0	.1170E+00	.6136E+00	.5847E+00	.5777E+00
6.0 - 8.0	.3188E+00	.8432E+00	.8247E+00	.8200E+00
8.0 - 10.0	.5229E+00	.9378E+00	.9281E+00	.9256E+00
10.0 - 12.0	.6838E+00	.9748E+00	.9701E+00	.9689E+00
12.0 - 15.0	.8161E+00	.9913E+00	.9894E+00	.9889E+00
15.0 - 18.0	.9066E+00	.9974E+00	.9968E+00	.9966E+00
18.0 - 21.0	.9525E+00	.9992E+00	.9989E+00	.9989E+00
21.0 - 24.0	.9755E+00	.9997E+00	.9996E+00	.9996E+00
24.0 - 27.0	.9871E+00	.9999E+00	.9999E+00	.9999E+00
27.0 - 30.0	.9931E+00	.1000E+01	.9999E+00	.9999E+00

Table A-5e

Mean Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS

CONDITION = PREDAMAGED

CATEGORY = E

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 0.25	0.25 - 0.35
0.5 - 2.5	.1868E-04	.9990E-02	.7195E-01	.5707E-01
2.5 - 4.0	.1452E-01	.3496E+00	.6840E+00	.6408E+00
4.0 - 6.0	.8653E-01	.6679E+00	.9031E+00	.8812E+00
6.0 - 8.0	.2376E+00	.8605E+00	.9743E+00	.9663E+00
8.0 - 10.0	.4061E+00	.9405E+00	.9923E+00	.9894E+00
10.0 - 12.0	.5564E+00	.9737E+00	.9975E+00	.9964E+00
12.0 - 15.0	.6993E+00	.9898E+00	.9993E+00	.9989E+00
15.0 - 18.0	.8162E+00	.9965E+00	.9998E+00	.9997E+00
18.0 - 21.0	.8879E+00	.9987E+00	.9999E+00	.9999E+00
21.0 - 24.0	.9312E+00	.9995E+00	.1000E+01	.1000E+01
24.0 - 27.0	.9573E+00	.9998E+00	.1000E+01	.1000E+01
27.0 - 30.0	.9731E+00	.9999E+00	.1000E+01	.1000E+01

Table A-6a

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS
CONDITION = PREDAMAGED
CATEGORY = A
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.3140E-12	.1002E-11	.2257E-11	.4659E-11
2.5 - 4.0	.4461E-06	.9974E-06	.1743E-05	.2861E-05
4.0 - 6.0	.5919E-04	.1124E-03	.1749E-03	.2585E-03
6.0 - 8.0	.1295E-02	.2169E-02	.3088E-02	.4209E-02
8.0 - 10.0	.8322E-02	.1273E-01	.1699E-01	.2186E-01
10.0 - 12.0	.2864E-01	.4084E-01	.5188E-01	.6382E-01
12.0 - 15.0	.8038E-01	.1070E+00	.1296E+00	.1527E+00
15.0 - 18.0	.1813E+00	.2266E+00	.2624E+00	.2972E+00
18.0 - 21.0	.3083E+00	.3667E+00	.4105E+00	.4511E+00
21.0 - 24.0	.4405E+00	.5041E+00	.5495E+00	.5901E+00
24.0 - 27.0	.5624E+00	.6244E+00	.6669E+00	.7036E+00
27.0 - 30.0	.6659E+00	.7220E+00	.7590E+00	.7900E+00

Table A-6b

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS
CONDITION = PREDAMAGED
CATEGORY = B
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.2744E-09	.9588E-09	.2179E-08	.4302E-08
2.5 - 4.0	.3364E-04	.7658E-04	.1305E-03	.2020E-03
4.0 - 6.0	.1616E-02	.3026E-02	.4523E-02	.6272E-02
6.0 - 8.0	.1672E-01	.2699E-01	.3655E-01	.4663E-01
8.0 - 10.0	.6394E-01	.9297E-01	.1174E+00	.1414E+00
10.0 - 12.0	.1491E+00	.2004E+00	.2402E+00	.2770E+00
12.0 - 15.0	.2903E+00	.3622E+00	.4138E+00	.4586E+00
15.0 - 18.0	.4716E+00	.5512E+00	.6039E+00	.6470E+00
18.0 - 21.0	.6291E+00	.7017E+00	.7467E+00	.7817E+00
21.0 - 24.0	.7494E+00	.8085E+00	.8431E+00	.8688E+00
24.0 - 27.0	.8346E+00	.8795E+00	.9044E+00	.9223E+00
27.0 - 30.0	.8922E+00	.9248E+00	.9421E+00	.9542E+00

Table A-6c

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS
CONDITION = PREDAMAGED
CATEGORY = C
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.5521E-03	.7943E-03	.9939E-03	.1851E-02
2.5 - 4.0	.1149E+00	.1363E+00	.1512E+00	.2000E+00
4.0 - 6.0	.4060E+00	.4466E+00	.4728E+00	.5482E+00
6.0 - 8.0	.6981E+00	.7333E+00	.7544E+00	.8100E+00
8.0 - 10.0	.8595E+00	.8813E+00	.8939E+00	.9246E+00
10.0 - 12.0	.9363E+00	.9482E+00	.9548E+00	.9702E+00
12.0 - 15.0	.9759E+00	.9812E+00	.9840E+00	.9902E+00
15.0 - 18.0	.9922E+00	.9942E+00	.9952E+00	.9973E+00
18.0 - 21.0	.9974E+00	.9981E+00	.9985E+00	.9992E+00
21.0 - 24.0	.9991E+00	.9993E+00	.9995E+00	.9997E+00
24.0 - 27.0	.9996E+00	.9998E+00	.9998E+00	.9999E+00
27.0 - 30.0	.9999E+00	.9999E+00	.9999E+00	.1000E+01

Table A-6d

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS

CONDITION = PREDAMAGED

CATEGORY = D

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.4080E-02	.1133E+00	.1002E+00	.9648E-01
2.5 - 4.0	.2404E+00	.7656E+00	.7433E+00	.7362E+00
4.0 - 6.0	.5792E+00	.9484E+00	.9404E+00	.9378E+00
6.0 - 8.0	.8189E+00	.9904E+00	.9884E+00	.9877E+00
8.0 - 10.0	.9246E+00	.9979E+00	.9974E+00	.9972E+00
10.0 - 12.0	.9683E+00	.9995E+00	.9993E+00	.9993E+00
12.0 - 15.0	.9887E+00	.9999E+00	.9999E+00	.9999E+00
15.0 - 18.0	.9965E+00	.1000E+01	.1000E+01	.1000E+01
18.0 - 21.0	.9988E+00	.1000E+01	.1000E+01	.1000E+01
21.0 - 24.0	.9996E+00	.1000E+01	.1000E+01	.1000E+01
24.0 - 27.0	.9998E+00	.1000E+01	.1000E+01	.1000E+01
27.0 - 30.0	.9999E+00	.1000E+01	.1000E+01	.1000E+01

Table A-6e

<u>Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Window</u>

MATERIAL TYPE = WINDOW GLASS
CONDITION = PREDAMAGED
CATEGORY = E
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.4003E-01	.5082E+00	.8106E+00	.7771E+00
2.5 - 4.0	.5312E+00	.9677E+00	.9966E+00	.9952E+00
4.0 - 6.0	.8149E+00	.9962E+00	.9998E+00	.9997E+00
6.0 - 8.0	.9383E+00	.9995E+00	.1000E+01	.1000E+01
8.0 - 10.0	.9781E+00	.9999E+00	.1000E+01	.1000E+01
10.0 - 12.0	.9917E+00	.1000E+01	.1000E+01	.1000E+01
12.0 - 15.0	.9972E+00	.1000E+01	.1000E+01	.1000E+01
15.0 - 18.0	.9992E+00	.1000E+01	.1000E+01	.1000E+01
18.0 - 21.0	.9997E+00	.1000E+01	.1000E+01	.1000E+01
21.0 - 24.0	.9999E+00	.1000E+01	.1000E+01	.1000E+01
24.0 - 27.0	.1000E+01	.1000E+01	.1000E+01	.1000E+01
27.0 - 30.0	.1000E+01	.1000E+01	.1000E+01	.1000E+01

Table A-7a

<u>Mean Estimates of Breakage Probabilities for Predamaged Window</u>

MATERIAL TYPE = WINDOW GLASS

CONDITION = PREDAMAGED

CATEGORY = A

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1257E-07	.2005E-07	.1102E-07	.7714E-08
2.5 - 4.0	.3331E-04	.4690E-04	.3024E-04	.2326E-04
4.0 - 6.0	.4534E-03	.6061E-03	.4177E-03	.3340E-03
6.0 - 8.0	.2648E-02	.3400E-02	.2467E-02	.2034E-02
8.0 - 10.0	.8212E-02	.1024E-01	.7713E-02	.6500E-02
10.0 - 12.0	.1833E-01	.2235E-01	.1733E-01	.1486E-01
12.0 - 15.0	.3764E-01	.4487E-01	.3580E-01	.3122E-01
15.0 - 18.0	.7084E-01	.8263E-01	.6779E-01	.6009E-01
18.0 - 21.0	.1126E+00	.1291E+00	.1083E+00	.9731E-01
21.0 - 24.0	.1604E+00	.1812E+00	.1549E+00	.1407E+00
24.0 - 27.0	.2117E+00	.2362E+00	.2052E+00	.1881E+00
27.0 - 30.0	.2643E+00	.2917E+00	.2568E+00	.2374E+00

Table A-7b

Mean Estimates of Breakage Probabilities for

Predamaged Window

MATERIAL TYPE = WINDOW GLASS

CONDITION = PREDAMAGED

CATEGORY = B

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec)			
	0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1922E-06	.6594E-06	.7650E-06	.3893E-06
2.5 - 4.0	.2445E-03	.5830E-03	.6467E-03	.4028E-03
4.0 - 6.0	.2444E-02	.5017E-02	.5464E-02	.3698E-02
6.0 - 8.0	.1122E-01	.2051E-01	.2202E-01	.1589E-01
8.0 - 10.0	.2921E-01	.4918E-01	.5227E-01	.3949E-01
10.0 - 12.0	.5686E-01	.8980E-01	.9470E-01	.7412E-01
12.0 - 15.0	.1021E+00	.1515E+00	.1585E+00	.1284E+00
15.0 - 18.0	.1686E+00	.2358E+00	.2450E+00	.2050E+00
18.0 - 21.0	.2414E+00	.3220E+00	.3327E+00	.2858E+00
21.0 - 24.0	.3152E+00	.4046E+00	.4162E+00	.3650E+00
24.0 - 27.0	.3866E+00	.4807E+00	.4925E+00	.4395E+00
27.0 - 30.0	.4533E+00	.5487E+00	.5604E+00	.5074E+00

Table A-7c

Mean Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS

CONDITION = PREDAMAGED

CATEGORY = C

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.6538E-04	.2702E-03	.4878E-03	.1064E-02
2.5 - 4.0	.1219E-01	.2965E-01	.4241E-01	.6711E-01
4.0 - 6.0	.5644E-01	.1112E+00	.1451E+00	.2027E+00
6.0 - 8.0	.1447E+00	.2438E+00	.2975E+00	.3798E+00
8.0 - 10.0	.2505E+00	.3791E+00	.4423E+00	.5321E+00
10.0 - 12.0	.3575E+00	.5000E+00	.5646E+00	.6511E+00
12.0 - 15.0	.4775E+00	.6212E+00	.6813E+00	.7571E+00
15.0 - 18.0	.5990E+00	.7310E+00	.7818E+00	.8423E+00
18.0 - 21.0	.6936E+00	.8082E+00	.8493E+00	.8960E+00
21.0 - 24.0	.7656E+00	.8620E+00	.8947E+00	.9303E+00
24.0 - 27.0	.8200E+00	.8998E+00	.9255E+00	.9524E+00
27.0 - 30.0	.8609E+00	.9264E+00	.9465E+00	.9670E+00

Table A-7d

Mean Estimates of Breakage Probabilities for

Predamaged Window

MATERIAL TYPE = WINDOW GLASS

CONDITION = PREDAMAGED

CATEGORY = D

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.9227E-04	.1197E-02	.5742E-02	.1565E-01
2.5 - 4.0	.1057E-01	.5450E-01	.1370E+00	.2359E+00
4.0 - 6.0	.4465E-01	.1596E+00	.3130E+00	.4550E+00
6.0 - 8.0	.1112E+00	.3025E+00	.4967E+00	.6429E+00
8.0 - 10.0	.1927E+00	.4344E+00	.6345E+00	.7637E+00
10.0 - 12.0	.2784E+00	.5459E+00	.7338E+00	.8410E+00
12.0 - 15.0	.3797E+00	.6541E+00	.8174E+00	.8997E+00
15.0 - 18.0	.4894E+00	.7505E+00	.8820E+00	.9406E+00
18.0 - 21.0	.5816E+00	.8183E+00	.9219E+00	.9634E+00
21.0 - 24.0	.6572E+00	.8660E+00	.9470E+00	.9768E+00
24.0 - 27.0	.7187E+00	.9000E+00	.9633E+00	.9848E+00
27.0 - 30.0	.7682E+00	.9245E+00	.9741E+00	.9898E+00

Table A-7e

Mean Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS

CONDITION = PREDAMAGED

CATEGORY = E

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.3507E-03	.2706E-02	.1480E-01	.4056E-01
2.5 - 4.0	.2511E-01	.8844E-01	.2283E+00	.3770E+00
4.0 - 6.0	.8804E-01	.2281E+00	.4447E+00	.6148E+00
6.0 - 8.0	.1909E+00	.3947E+00	.6327E+00	.7794E+00
8.0 - 10.0	.3004E+00	.5336E+00	.7550E+00	.8690E+00
10.0 - 12.0	.4038E+00	.6421E+00	.8340E+00	.9194E+00
12.0 - 15.0	.5148E+00	.7404E+00	.8945E+00	.9537E+00
15.0 - 18.0	.6241E+00	.8222E+00	.9370E+00	.9751E+00
18.0 - 21.0	.7082E+00	.8762E+00	.9610E+00	.9859E+00
21.0 - 24.0	.7724E+00	.9122E+00	.9750E+00	.9916E+00
24.0 - 27.0	.8213E+00	.9368E+00	.9836E+00	.9948E+00
27.0 - 30.0	.8586E+00	.9537E+00	.9889E+00	.9967E+00

Table A-8a

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS
CONDITION = PREDAMAGED
CATEGORY = A
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.5857E-05	.8255E-05	.5090E-05	.3805E-05
2.5 - 4.0	.1571E-02	.1993E-02	.1417E-02	.1152E-02
4.0 - 6.0	.1109E-01	.1345E-01	.1020E-01	.8615E-02
6.0 - 8.0	.3890E-01	.4558E-01	.3630E-01	.3158E-01
8.0 - 10.0	.8427E-01	.9635E-01	.7948E-01	.7060E-01
10.0 - 12.0	.1427E+00	.1601E+00	.1357E+00	.1225E+00
12.0 - 15.0	.2247E+00	.2476E+00	.2153E+00	.1974E+00
15.0 - 18.0	.3270E+00	.3542E+00	.3156E+00	.2936E+00
18.0 - 21.0	.4239E+00	.4531E+00	.4115E+00	.3873E+00
21.0 - 24.0	.5110E+00	.5405E+00	.4983E+00	.4733E+00
24.0 - 27.0	.5868E+00	.6155E+00	.5744E+00	.5497E+00
27.0 - 30.0	.6515E+00	.6786E+00	.6397E+00	.6160E+00

Table A-8b

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS
CONDITION = PREDAMAGED
CATEGORY = B
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.4559E-04	.1153E-03	.1295E-03	.7618E-04
2.5 - 4.0	.6507E-02	.1207E-01	.1303E-01	.9156E-02
4.0 - 6.0	.3476E-01	.5632E-01	.5974E-01	.4543E-01
6.0 - 8.0	.9858E-01	.1443E+00	.1511E+00	.1219E+00
8.0 - 10.0	.1836E+00	.2504E+00	.2599E+00	.2184E+00
10.0 - 12.0	.2769E+00	.3581E+00	.3692E+00	.3199E+00
12.0 - 15.0	.3901E+00	.4798E+00	.4916E+00	.4384E+00
15.0 - 18.0	.5120E+00	.6020E+00	.6133E+00	.5612E+00
18.0 - 21.0	.6130E+00	.6969E+00	.7072E+00	.6595E+00
21.0 - 24.0	.6941E+00	.7691E+00	.7780E+00	.7361E+00
24.0 - 27.0	.7580E+00	.8234E+00	.8310E+00	.7950E+00
27.0 - 30.0	.8080E+00	.8641E+00	.8704E+00	.8400E+00

Table A-8c

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS
CONDITION = PREDAMAGED
CATEGORY = C
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.6844E-02	.1746E-01	.2581E-01	.4292E-01
2.5 - 4.0	.1532E+00	.2521E+00	.3069E+00	.3913E+00
4.0 - 6.0	.3592E+00	.4978E+00	.5626E+00	.6504E+00
6.0 - 8.0	.5638E+00	.6969E+00	.7514E+00	.8180E+00
8.0 - 10.0	.7072E+00	.8160E+00	.8562E+00	.9019E+00
10.0 - 12.0	.8029E+00	.8863E+00	.9147E+00	.9451E+00
12.0 - 15.0	.8773E+00	.9353E+00	.9535E+00	.9718E+00
15.0 - 18.0	.9289E+00	.9658E+00	.9765E+00	.9866E+00
18.0 - 21.0	.9575E+00	.9811E+00	.9875E+00	.9932E+00
21.0 - 24.0	.9738E+00	.9891E+00	.9930E+00	.9964E+00
24.0 - 27.0	.9835E+00	.9935E+00	.9960E+00	.9980E+00
27.0 - 30.0	.9893E+00	.9960E+00	.9976E+00	.9988E+00

Table A-8d

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS
CONDITION = PREDAMAGED
CATEGORY = D
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.4687E-02	.2792E-01	.7949E-01	.1517E+00
2.5 - 4.0	.9754E-01	.2703E+00	.4566E+00	.6068E+00
4.0 - 6.0	.2443E+00	.4964E+00	.6894E+00	.8089E+00
6.0 - 8.0	.4136E+00	.6791E+00	.8335E+00	.9112E+00
8.0 - 10.0	.5524E+00	.7925E+00	.9063E+00	.9553E+00
10.0 - 12.0	.6595E+00	.8632E+00	.9449E+00	.9760E+00
12.0 - 15.0	.7559E+00	.9157E+00	.9699E+00	.9881E+00
15.0 - 18.0	.8345E+00	.9511E+00	.9846E+00	.9944E+00
18.0 - 21.0	.8857E+00	.9705E+00	.9916E+00	.9972E+00
21.0 - 24.0	.9196E+00	.9815E+00	.9952E+00	.9985E+00
24.0 - 27.0	.9425E+00	.9881E+00	.9971E+00	.9992E+00
27.0 - 30.0	.9582E+00	.9921E+00	.9982E+00	.9995E+00

Table A-8e

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Window

MATERIAL TYPE = WINDOW GLASS
CONDITION = PREDAMAGED
CATEGORY = E
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1529E-01	.6347E-01	.1713E+00	.3001E+00
2.5 - 4.0	.1970E+00	.4157E+00	.6410E+00	.7839E+00
4.0 - 6.0	.4013E+00	.6514E+00	.8323E+00	.9174E+00
6.0 - 8.0	.5885E+00	.8060E+00	.9246E+00	.9686E+00
8.0 - 10.0	.7168E+00	.8874E+00	.9630E+00	.9865E+00
10.0 - 12.0	.8029E+00	.9321E+00	.9806E+00	.9936E+00
12.0 - 15.0	.8715E+00	.9619E+00	.9905E+00	.9972E+00
15.0 - 18.0	.9210E+00	.9799E+00	.9957E+00	.9989E+00
18.0 - 21.0	.9499E+00	.9888E+00	.9979E+00	.9995E+00
21.0 - 24.0	.9672E+00	.9935E+00	.9989E+00	.9997E+00
24.0 - 27.0	.9781E+00	.9960E+00	.9994E+00	.9999E+00
27.0 - 30.0	.9849E+00	.9975E+00	.9996E+00	.9999E+00

Table A-9a

Mean Estimates of Breakage Probabilities for Plaster Structural Element

MATERIAL TYPE = PLASTER

CONDITION = HEALTHY

CATEGORY = A

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.7028E-09	.3798E-09	.8834E-09	.1921E-08
2.5 - 4.0	.4920E-04	.3264E-04	.5726E-04	.9555E-04
4.0 - 6.0	.1438E-02	.1038E-02	.1621E-02	.2426E-02
6.0 - 8.0	.1195E-01	.9211E-02	.1315E-01	.1810E-01
8.0 - 10.0	.4198E-01	.3389E-01	.4540E-01	.5890E-01
10.0 - 12.0	.9584E-01	.8016E-01	.1023E+00	.1268E+00
12.0 - 15.0	.1889E+00	.1635E+00	.1991E+00	.2364E+00
15.0 - 18.0	.3226E+00	.2882E+00	.3360E+00	.3835E+00
18.0 - 21.0	.4563E+00	.4175E+00	.4709E+00	.5216E+00
21.0 - 24.0	.5754E+00	.5365E+00	.5898E+00	.6384E+00
24.0 - 27.0	.6744E+00	.6383E+00	.6876E+00	.7311E+00
27.0 - 30.0	.7531E+00	.7210E+00	.7646E+00	.8019E+00

Table A-9b

Mean Estimates of Breakage Probabilities for Plaster Structural Element

MATERIAL TYPE = PLASTER

CONDITION = HEALTHY

CATEGORY = B

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.2220E-15	.4441E-15	.8882E-15
2.5 - 4.0	.6107E-09	.2459E-08	.4741E-08	.7112E-08
4.0 - 6.0	.1611E-06	.5237E-06	.9106E-06	.1280E-05
6.0 - 8.0	.6946E-05	.1911E-04	.3064E-04	.4095E-04
8.0 - 10.0	.7721E-04	.1880E-03	.2844E-03	.3664E-03
10.0 - 12.0	.4242E-03	.9387E-03	.1355E-02	.1697E-02
12.0 - 15.0	.1939E-02	.3904E-02	.5385E-02	.6551E-02
15.0 - 18.0	.7314E-02	.1342E-01	.1770E-01	.2095E-01
18.0 - 21.0	.1921E-01	.3268E-01	.4158E-01	.4811E-01
21.0 - 24.0	.3982E-01	.6360E-01	.7853E-01	.8916E-01
24.0 - 27.0	.7007E-01	.1061E+00	.1277E+00	.1427E+00
27.0 - 30.0	.1094E+00	.1582E+00	.1863E+00	.2053E+00

Table A-9c

Mean Estimates of Breakage Probabilities for Plaster Structural Element

MATERIAL TYPE = PLASTER

CONDITION = HEALTHY

CATEGORY = C

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.0000E+00	.2220E-15	.7772E-15	.1332E-14
2.5 - 4.0	.6336E-09	.2615E-08	.5470E-08	.8702E-08
4.0 - 6.0	.1582E-06	.5261E-06	.9805E-06	.1449E-05
6.0 - 8.0	.6611E-05	.1857E-04	.3163E-04	.4412E-04
8.0 - 10.0	.7232E-04	.1797E-03	.2866E-03	.3834E-03
10.0 - 12.0	.3938E-03	.8884E-03	.1346E-02	.1742E-02
12.0 - 15.0	.1791E-02	.3672E-02	.5285E-02	.6622E-02
15.0 - 18.0	.6743E-02	.1258E-01	.1723E-01	.2092E-01
18.0 - 21.0	.1773E-01	.3065E-01	.4032E-01	.4770E-01
21.0 - 24.0	.3683E-01	.5976E-01	.7599E-01	.8802E-01
24.0 - 27.0	.6504E-01	.9993E-01	.1235E+00	.1405E+00
27.0 - 30.0	.1020E+00	.1495E+00	.1803E+00	.2019E+00

Table A-9d

Mean Estimates of Breakage Probabilities for Plaster Structural Element

MATERIAL TYPE = PLASTER

CONDITION = HEALTHY

CATEGORY = D

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.2958E-11	.1211E-10	.2998E-10	.5261E-10
2.5 - 4.0	.1854E-05	.4858E-05	.8963E-05	.1307E-04
4.0 - 6.0	.1196E-03	.2604E-03	.4255E-03	.5749E-03
6.0 - 8.0	.1750E-02	.3302E-02	.4911E-02	.6254E-02
8.0 - 10.0	.8984E-02	.1529E-01	.2126E-01	.2596E-01
10.0 - 12.0	.2709E-01	.4257E-01	.5621E-01	.6644E-01
12.0 - 15.0	.6902E-01	.1004E+00	.1261E+00	.1444E+00
15.0 - 18.0	.1484E+00	.2006E+00	.2403E+00	.2674E+00
18.0 - 21.0	.2491E+00	.3179E+00	.3671E+00	.3994E+00
21.0 - 24.0	.3578E+00	.4362E+00	.4894E+00	.5232E+00
24.0 - 27.0	.4638E+00	.5450E+00	.5976E+00	.6299E+00
27.0 - 30.0	.5602E+00	.6387E+00	.6877E+00	.7170E+00

Table A-10a

Mean Plus One Sigma Estimates of Breakage Probabilities for Plaster Structural Elements

MATERIAL TYPE = PLASTER

CONDITION = HEALTHY

CATEGORY = A

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.2487E-06	.1431E-06	.2891E-06	.5533E-06
2.5 - 4.0	.5753E-03	.3900E-03	.6260E-03	.9669E-03
4.0 - 6.0	.9414E-02	.6984E-02	.1003E-01	.1395E-01
6.0 - 8.0	.5002E-01	.3970E-01	.5249E-01	.6750E-01
8.0 - 10.0	.1311E+00	.1092E+00	.1361E+00	.1656E+00
10.0 - 12.0	.2411E+00	.2083E+00	.2484E+00	.2902E+00
12.0 - 15.0	.3916E+00	.3502E+00	.4006E+00	.4501E+00
15.0 - 18.0	.5567E+00	.5132E+00	.5659E+00	.6150E+00
18.0 - 21.0	.6883E+00	.6485E+00	.6964E+00	.7391E+00
21.0 - 24.0	.7851E+00	.7517E+00	.7918E+00	.8262E+00
24.0 - 27.0	.8533E+00	.8266E+00	.8586E+00	.8850E+00
27.0 - 30.0	.9001E+00	.8795E+00	.9041E+00	.9239E+00

Table A-10b

Mean Plus One Sigma Estimates of Breakage Probabilities for Plaster Structural Elements

MATERIAL TYPE = PLASTER

CONDITION = HEALTHY

CATEGORY = B

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec)			
	0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1753E-11	.8501E-11	.1801E-10	.2865E-10
2.5 - 4.0	.3668E-06	.1142E-05	.1953E-05	.2716E-05
4.0 - 6.0	.3271E-04	.8274E-04	.1279E-03	.1669E-03
6.0 - 8.0	.5998E-03	.1202E-02	.1848E-02	.2298E-02
8.0 - 10.0	.3662E-02	.7025E-02	.9492E-02	.1140E-01
10.0 - 12.0	.1265E-01	.2217E-01	.2867E-01	.3349E-01
12.0 - 15.0	.3708E-01	.5939E-01	.7356E-01	.8367E-01
15.0 - 18.0	.8987E-01	.1322E+00	.1573E+00	.1745E+00
18.0 - 21.0	.1656E+00	.2278E+00	.2624E+00	.2854E+00
21.0 - 24.0	.2562E+00	.3338E+00	.3748E+00	.4012E+00
24.0 - 27.0	.3527E+00	.4395E+00	.4832E+00	.5107E+00
27.0 - 30.0	.4472E+00	.5371E+00	.5805E+00	.6073E+00

Table A-10c

Mean Plus One Sigma Estimates of Breakage Probabilities for Plaster Structural Elements

MATERIAL TYPE = PLASTER

CONDITION = HEALTHY

CATEGORY = C

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.2117E-11	.1045E-10	.2426E-10	.4122E-10
2.5 - 4.0	.3868E-06	.1221E-05	.2230E-05	.3251E-05
4.0 - 6.0	.3287E-04	.8423E-04	.1374E-03	.1864E-03
6.0 - 8.0	.5874E-03	.1281E-02	.1916E-02	.2459E-02
8.0 - 10.0	.3540E-02	.6870E-02	.9646E-02	.1190E-01
10.0 - 12.0	.1215E-01	.2153E-01	.2878E-01	.3440E-01
12.0 - 15.0	.3549E-01	.5745E-01	.7319E-01	.8487E-01
15.0 - 18.0	.8601E-01	.1278E+00	.1556E+00	.1754E+00
18.0 - 21.0	.1588E+00	.2205E+00	.2590E+00	.2854E+00
21.0 - 24.0	.2464E+00	.3239E+00	.3697E+00	.4000E+00
24.0 - 27.0	.3403E+00	.4276E+00	.4767E+00	.5084E+00
27.0 - 30.0	.4331E+00	.5241E+00	.5732E+00	.6041E+00

Table A-10d

Mean Plus One Sigma Estimates of Breakage Probabilities for Plaster Structural Elements

MATERIAL TYPE = PLASTER
CONDITION = HEALTHY
CATEGORY = D
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.2029E-07	.6219E-07	.1283E-06	.2006E-06
2.5 - 4.0	.2221E-03	.4641E-03	.7431E-03	.9911E-03
4.0 - 6.0	.5144E-02	.9011E-02	.1284E-01	.1591E-01
6.0 - 8.0	.3412E-01	.5235E-01	.6831E-01	.8016E-01
8.0 - 10.0	.1013E+00	.1416E+00	.1738E+00	.1963E+00
10.0 - 12.0	.2017E+00	.2628E+00	.3084E+00	.3387E+00
12.0 - 15.0	.3479E+00	.4246E+00	.4777E+00	.5113E+00
15.0 - 18.0	.5187E+00	.5978E+00	.6487E+00	.6794E+00
18.0 - 21.0	.6596E+00	.7298E+00	.7722E+00	.7969E+00
21.0 - 24.0	.7653E+00	.8223E+00	.8550E+00	.8734E+00
24.0 - 27.0	.8405E+00	.8844E+00	.9085E+00	.9216E+00
27.0 - 30.0	.8922E+00	.9249E+00	.9422E+00	.9513E+00

Table A-11a

Mean Estimates of Breakage Probabilities for Plaster Structural Element

MATERIAL TYPE = PLASTER
CONDITION = HEALTHY
CATEGORY = A
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.5074E-07	.1983E-05	.5792E-05	.1324E-04
2.5 - 4.0	.7345E-04	.1017E-02	.2136E-02	.3750E-02
4.0 - 6.0	.8162E-03	.7363E-02	.1351E-01	.2130E-01
6.0 - 8.0	.4153E-02	.2690E-01	.4452E-01	.6464E-01
8.0 - 10.0	.1178E-01	.6019E-01	.9255E-01	.1268E+00
10.0 - 12.0	.2468E-01	.1048E+00	.1523E+00	.1996E+00
12.0 - 15.0	.4788E-01	.1699E+00	.2337E+00	.2935E+00
15.0 - 18.0	.8571E-01	.2557E+00	.3341E+00	.4032E+00
18.0 - 21.0	.1314E+00	.3414E+00	.4283E+00	.5011E+00
21.0 - 24.0	.1820E+00	.4220E+00	.5125E+00	.5850E+00
24.0 - 27.0	.2350E+00	.4955E+00	.5857E+00	.6555E+00
27.0 - 30.0	.2883E+00	.5607E+00	.6483E+00	.7137E+00

Table A-11b

Mean Estimates of Breakage Probabilities for Plaster Structural Element

MATERIAL TYPE = PLASTER
CONDITION = HEALTHY
CATEGORY = B
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.4503E-08	.2008E-07	.4953E-07	.8947E-07
2.5 - 4.0	.1163E-04	.3552E-04	.6918E-04	.1067E-03
4.0 - 6.0	.1657E-03	.4327E-03	.7641E-03	.1104E-02
6.0 - 8.0	.1027E-02	.2373E-02	.3882E-02	.5330E-02
8.0 - 10.0	.3368E-02	.7119E-02	.1103E-01	.1459E-01
10.0 - 12.0	.7913E-02	.1560E-01	.2314E-01	.2976E-01
12.0 - 15.0	.1720E-01	.3167E-01	.4502E-01	.5629E-01
15.0 - 18.0	.3444E-01	.5929E-01	.8090E-01	.9843E-01
18.0 - 21.0	.5785E-01	.9432E-01	.1245E+00	.1481E+00
21.0 - 24.0	.8654E-01	.1348E+00	.1730E+00	.2022E+00
24.0 - 27.0	.1193E+00	.1788E+00	.2242E+00	.2579E+00
27.0 - 30.0	.1550E+00	.2245E+00	.2759E+00	.3132E+00

Table A-11c

Mean Estimates of Breakage Probabilities for Plaster Structural Element

MATERIAL TYPE = PLASTER
CONDITION = HEALTHY
CATEGORY = C
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec)			
	0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1143E-08	.6281E-08	.1921E-07	.3914E-07
2.5 - 4.0	.4967E-05	.1779E-04	.4067E-04	.6851E-04
4.0 - 6.0	.8500E-04	.2548E-03	.5161E-03	.8033E-03
6.0 - 8.0	.5991E-03	.1563E-02	.2881E-02	.4218E-02
8.0 - 10.0	.2140E-02	.5048E-02	.8691E-02	.1217E-01
10.0 - 12.0	.5352E-02	.1167E-01	.1904E-01	.2577E-01
12.0 - 15.0	.1233E-01	.2486E-01	.3849E-01	.5035E-01
15.0 - 18.0	.2602E-01	.4861E-01	.7153E-01	.9052E-01
18.0 - 21.0	.4550E-01	.7989E-01	.1128E+00	.1390E+00
21.0 - 24.0	.7025E-01	.1171E+00	.1597E+00	.1925E+00
24.0 - 27.0	.9941E-01	.1585E+00	.2099E+00	.2483E+00
27.0 - 30.0	.1319E+00	.2023E+00	.2613E+00	.3042E+00

Table A-11d

Mean Estimates of Breakage Probabilities for Plaster Structural Element

MATERIAL TYPE = PLASTER

CONDITION = HEALTHY

CATEGORY = D

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.2081E-06	.9900E-06	.2345E-05	.4919E-05
2.5 - 4.0	.2337E-03	.7047E-03	.1283E-02	.2132E-02
4.0 - 6.0	.2271E-02	.5674E-02	.9274E-02	.1401E-01
6.0 - 8.0	.1029E-01	.2224E-01	.3346E-01	.4700E-01
8.0 - 10.0	.2670E-01	.5200E-01	.7375E-01	.9837E-01
10.0 - 12.0	.5196E-01	.9340E-01	.1266E+00	.1622E+00
12.0 - 15.0	.9348E-01	.1554E+00	.2015E+00	.2486E+00
15.0 - 18.0	.1551E+00	.2393E+00	.2976E+00	.3542E+00
18.0 - 21.0	.2233E+00	.3245E+00	.3905E+00	.4521E+00
21.0 - 24.0	.2931E+00	.4058E+00	.4757E+00	.5384E+00
24.0 - 27.0	.3614E+00	.4806E+00	.5512E+00	.6126E+00
27.0 - 30.0	.4259E+00	.5474E+00	.6165E+00	.6751E+00

Table A-12a

Mean Plus One Sigma Estimates of Breakage Probabilities for Plaster Structural Elements

MATERIAL TYPE = PLASTER

CONDITION = HEALTHY

CATEGORY = A

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.3473E-05	.6881E-04	.1682E-03	.3344E-03
2.5 - 4.0	.7082E-03	.5881E-02	.1093E-01	.1746E-01
4.0 - 6.0	.5365E-02	.3007E-01	.4914E-01	.7081E-01
6.0 - 8.0	.2018E-01	.8394E-01	.1245E+00	.1662E+00
8.0 - 10.0	.4661E-01	.1567E+00	.2173E+00	.2749E+00
10.0 - 12.0	.8352E-01	.2385E+00	.3139E+00	.3816E+00
12.0 - 15.0	.1400E+00	.3411E+00	.4274E+00	.5001E+00
15.0 - 18.0	.2165E+00	.4548E+00	.5450E+00	.6165E+00
18.0 - 21.0	.2955E+00	.5530E+00	.6404E+00	.7065E+00
21.0 - 24.0	.3723E+00	.6348E+00	.7160E+00	.7747E+00
24.0 - 27.0	.4440E+00	.7017E+00	.7751E+00	.8262E+00
27.0 - 30.0	.5091E+00	.7559E+00	.8211E+00	.8650E+00

Table A-12b

Mean Plus One Sigma Estimates of Breakage Probabilities for Plaster Structural Elements

MATERIAL TYPE = PLASTER

CONDITION = HEALTHY

CATEGORY = B

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1298E-05	.4201E-05	.8823E-05	.1424E-04
2.5 - 4.0	.4087E-03	.9565E-03	.1634E-02	.2298E-02
4.0 - 6.0	.3372E-02	.6833E-02	.1061E-01	.1402E-01
6.0 - 8.0	.1361E-01	.2470E-01	.3569E-01	.4496E-01
8.0 - 10.0	.3301E-01	.5535E-01	.7593E-01	.9247E-01
10.0 - 12.0	.6144E-01	.9687E-01	.1276E+00	.1514E+00
12.0 - 15.0	.1068E+00	.1585E+00	.2008E+00	.2323E+00
15.0 - 18.0	.1713E+00	.2401E+00	.2933E+00	.3312E+00
18.0 - 21.0	.2408E+00	.3226E+00	.3827E+00	.4242E+00
21.0 - 24.0	.3108E+00	.4012E+00	.4648E+00	.5076E+00
24.0 - 27.0	.3784E+00	.4735E+00	.5380E+00	.5803E+00
27.0 - 30.0	.4416E+00	.5383E+00	.6019E+00	.6426E+00

Table A-12c

Mean Plus One Sigma Estimates of Breakage

Probabilities for Plaster Structural Elements

MATERIAL TYPE = PLASTER

CONDITION = HEALTHY

CATEGORY = C

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec)			
	0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.3384E-06	.1301E-05	.3299E-05	.5935E-05
2.5 - 4.0	.1640E-03	.4[illegible]77E-03	.8618E-03	.1315E-02
4.0 - 6.0	.1651E-02	.3749E-02	.6565E-02	.9286E-02
6.0 - 8.0	.7664E-02	.1537E-01	.2460E-01	.3284E-01
8.0 - 10.0	.2043E-01	.3746E-01	.5623E-01	.7200E-01
10.0 - 12.0	.4078E-01	.6973E-01	.9955E-01	.1234E+00
12.0 - 15.0	.7567E-01	.1208E+00	.1642E+00	.1974E+00
15.0 - 18.0	.1288E+00	.1926E+00	.2499E+00	.2917E+00
18.0 - 21.0	.1893E+00	.2688E+00	.3362E+00	.3834E+00
21.0 - 24.0	.2531E+00	.3443E+00	.4179E+00	.4677E+00
24.0 - 27.0	.3170E+00	.4160E+00	.4926E+00	.5429E+00
27.0 - 30.0	.3786E+00	.4820E+00	.5590E+00	.6082E+00

Table A-12d

Mean Plus One Sigma Estimates of Breakage Probabilities for Plaster Structural Elements

MATERIAL TYPE = PLASTER

CONDITION = HEALTHY

CATEGORY = D

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + 1.000 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.2458E-04	.8109E-04	.1625E-03	.2935E-03
2.5 - 4.0	.3667E-02	.8253E-02	.1319E-01	.1953E-01
4.0 - 6.0	.2142E-01	.4079E-01	.5884E-01	.7962E-01
6.0 - 8.0	.6551E-01	.1100E+00	.1469E+00	.1860E+00
8.0 - 10.0	.1294E+00	.1988E+00	.2518E+00	.3043E+00
10.0 - 12.0	.2047E+00	.2940E+00	.3576E+00	.4177E+00
12.0 - 15.0	.3025E+00	.4076E+00	.4774E+00	.5399E+00
15.0 - 18.0	.4154E+00	.5278E+00	.5974E+00	.6567E+00
18.0 - 21.0	.5155E+00	.6264E+00	.6912E+00	.7441E+00
21.0 - 24.0	.6008E+00	.7049E+00	.7629E+00	.8085E+00
24.0 - 27.0	.6717E+00	.7666E+00	.8172E+00	.8558E+00
27.0 - 30.0	.7298E+00	.8147E+00	.8582E+00	.8905E+00

Table A-13a

Mean Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER

CONDITION = PREDAMAGED

CATEGORY = A

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressuer Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1947E-03	.1334E-03	.2238E-03	.3583E-03
2.5 - 4.0	.8280E-01	.6880E-01	.8859E-01	.1108E+00
4.0 - 6.0	.3182E+00	.2840E+00	.3315E+00	.3788E+00
6.0 - 8.0	.5985E+00	.5601E+00	.6127E+00	.6604E+00
8.0 - 10.0	.7823E+00	.7523E+00	.7930E+00	.8274E+00
10.0 - 12.0	.8854E+00	.8652E+00	.8924E+00	.9141E+00
12.0 - 15.0	.9481E+00	.9367E+00	.9519E+00	.9633E+00
15.0 - 18.0	.9797E+00	.9744E+00	.9815E+00	.9865E+00
18.0 - 21.0	.9918E+00	.9893E+00	.9926E+00	.9948E+00
21.0 - 24.0	.9965E+00	.9953E+00	.9969E+00	.9979E+00
24.0 - 27.0	.9985E+00	.9979E+00	.9986E+00	.9991E+00
27.0 - 30.0	.9993E+00	.9990E+00	.9994E+00	.9996E+00

Table A-13b

Mean Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER
CONDITION = PREDAMAGED
CATEGORY = B
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.5658E-08	.2100E-07	.3892E-07	.5696E-07
2.5 - 4.0	.3107E-03	.7002E-03	.1020E-02	.1284E-02
4.0 - 6.0	.7055E-02	.1298E-01	.1714E-01	.2030E-01
6.0 - 8.0	.4553E-01	.7183E-01	.8818E-01	.9975E-01
8.0 - 10.0	.1297E+00	.1839E+00	.2147E+00	.2354E+00
10.0 - 12.0	.2480E+00	.3252E+00	.3658E+00	.3921E+00
12.0 - 15.0	.4083E+00	.4982E+00	.5421E+00	.5694E+00
15.0 - 18.0	.5849E+00	.6708E+00	.7096E+00	.7328E+00
18.0 - 21.0	.7209E+00	.7919E+00	.8221E+00	.8395E+00
21.0 - 24.0	.8168E+00	.8709E+00	.8927E+00	.9049E+00
24.0 - 27.0	.8811E+00	.9205E+00	.9355E+00	.9438E+00
27.0 - 30.0	.9231E+00	.9509E+00	.9611E+00	.9666E+00

Table A-13c

Mean Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER

CONDITION = PREDAMAGED

CATEGORY = C

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.5737E-08	.2181E-07	.4366E-07	.6752E-07
2.5 - 4.0	.2889E-03	.6638E-03	.1015E-02	.1322E-02
4.0 - 6.0	.6504E-02	.1217E-01	.1669E-01	.2028E-01
6.0 - 8.0	.4214E-01	.6753E-01	.8531E-01	.9840E-01
8.0 - 10.0	.1210E+00	.1741E+00	.2079E+00	.2314E+00
10.0 - 12.0	.2336E+00	.3103E+00	.3554E+00	.3854E+00
12.0 - 15.0	.3888E+00	.4798E+00	.5293E+00	.5608E+00
15.0 - 18.0	.5634E+00	.6523E+00	.6970E+00	.7241E+00
18.0 - 21.0	.7009E+00	.7761E+00	.8114E+00	.8321E+00
21.0 - 24.0	.8000E+00	.8585E+00	.8845E+00	.8992E+00
24.0 - 27.0	.8679E+00	.9112E+00	.9296E+00	.9397E+00
27.0 - 30.0	.9130E+00	.9443E+00	.9569E+00	.9637E+00

Table A-13d

Mean Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER

CONDITION = PREDAMAGED

CATEGORY = D

WAVE TYPE = N-WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1001E-04	.2443E-04	.4304E-04	.6096E-04
2.5 - 4.0	.2223E-01	.3546E-01	.4729E-01	.5624E-01
4.0 - 6.0	.1455E+00	.1971E+00	.2364E+00	.2632E+00
6.0 - 8.0	.3812E+00	.4607E+00	.5142E+00	.5478E+00
8.0 - 10.0	.5992E+00	.6755E+00	.7222E+00	.7498E+00
10.0 - 12.0	.7556E+00	.8149E+00	.8486E+00	.8675E+00
12.0 - 15.0	.8717E+00	.9096E+00	.9296E+00	.9403E+00
15.0 - 18.0	.9423E+00	.9623E+00	.9721E+00	.9771E+00
18.0 - 21.0	.9738E+00	.9840E+00	.9886E+00	.9909E+00
21.0 - 24.0	.9879E+00	.9930E+00	.9952E+00	.9963E+00
24.0 - 27.0	.9942E+00	.9968E+00	.9979E+00	.9984E+00
27.0 - 30.0	.9972E+00	.9985E+00	.9991E+00	.9993E+00

Table A-14a

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER
CONDITION = PREDAMAGED
CATEGORY = A
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.5876E-02	.4340E-02	.6378E-02	.9045E-02
2.5 - 4.0	.2288E+00	.1972E+00	.2362E+00	.2769E+00
4.0 - 6.0	.5633E+00	.5200E+00	.5726E+00	.6216E+00
6.0 - 8.0	.8061E+00	.7746E+00	.8125E+00	.8446E+00
8.0 - 10.0	.9172E+00	.8992E+00	.9207E+00	.9378E+00
10.0 12.0	.9645E+00	.9550E+00	.9663E+00	.9747E+00
12.0 - 15.0	.9872E+00	.9831E+00	.9880E+00	.9914E+00
15.0 - 18.0	.9960E+00	.9945E+00	.9963E+00	.9974E+00
18.0 - 21.0	.9986E+00	.9981E+00	.9987E+00	.9992E+00
21.0 - 24.0	.9995E+00	.9993E+00	.9996E+00	.9997E+00
24.0 - 27.0	.9998E+00	.9997E+00	.9998E+00	.9999E+00
27.0 - 30.0	.9999E+00	.9999E+00	.9999E+00	.1000E+01

Table A-14b

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER
CONDITION = PREDAMAGED
CATEGORY = B
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.8516E-05	.2306E-04	.3680E-04	.4903E-04
2.5 - 4.0	.1082E-01	.1919E-01	.2496E-01	.2926E-01
4.0 - 6.0	.9068E-01	.1333E+00	.1585E+00	.1758E+00
6.0 - 8.0	.2799E+00	.3604E+00	.4024E+00	.4293E+00
8.0 - 10.0	.4897E+00	.5792E+00	.6217E+00	.6477E+00
10.0 - 12.0	.6625E+00	.7405E+00	.7749E+00	.7951E+00
12.0 - 15.0	.8079E+00	.8635E+00	.8861E+00	.8989E+00
15.0 - 18.0	.9056E+00	.9382E+00	.9506E+00	.9572E+00
18.0 - 21.0	.9539E+00	.9719E+00	.9783E+00	.9816E+00
21.0 - 24.0	.9773E+00	.9870E+00	.9903E+00	.9919E+00
24.0 - 27.0	.9886E+00	.9939E+00	.9955E+00	.9963E+00
27.0 - 30.0	.9942E+00	.9970E+00	.9979E+00	.9983E+00

Table A-14c

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER
CONDITION = PREDAMAGED
CATEGORY = C
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.8554E-05	.2350E-04	.3976E-04	.5521E-04
2.5 - 4.0	.1039E-01	.1863E-01	.2507E-01	.3010E-01
4.0 - 6.0	.8674E-01	.1288E+00	.1568E+00	.1766E+00
6.0 - 8.0	.2694E+00	.3499E+00	.3968E+00	.4277E+00
8.0 - 10.0	.4750E+00	.5660E+00	.6142E+00	.6442E+00
10.0 - 12.0	.6473E+00	.7281E+00	.7677E+00	.7912E+00
12.0 - 15.0	.7952E+00	.8540E+00	.8806E+00	.8957E+00
15.0 - 18.0	.8970E+00	.9323E+00	.9471E+00	.9552E+00
18.0 - 21.0	.9485E+00	.9685E+00	.9764E+00	.9805E+00
21.0 - 24.0	.9741E+00	.9851E+00	.9892E+00	.9913E+00
24.0 - 27.0	.9867E+00	.9928E+00	.9949E+00	.9960E+00
27.0 - 30.0	.9931E+00	.9964E+00	.9976E+00	.9981E+00

Table A-14d

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER
CONDITION = PREDAMAGED
CATEGORY = D
WAVE TYPE = N-WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.2045E-02	.3797E-02	.5613E-02	.7122E-02
2.5 - 4.0	.1855E+00	.2439E+00	.2878E+00	.3173E+00
4.0 - 6.0	.5206E+00	.5997E+00	.6505E+00	.6812E+00
6.0 - 8.0	.7865E+00	.8402E+00	.8706E+00	.8876E+00
8.0 - 10.0	.9105E+00	.9388E+00	.9534E+00	.9610E+00
10.0 - 12.0	.9626E+00	.9763E+00	.9829E+00	.9862E+00
12.0 - 15.0	.9870E+00	.9924E+00	.9948E+00	.9959E+00
15.0 - 18.0	.9961E+00	.9979E+00	.9986E+00	.9990E+00
18.0 - 21.0	.9988E+00	.9994E+00	.9996E+00	.9997E+00
21.0 - 24.0	.9996E+00	.9998E+00	.9999E+00	.9999E+00
24.0 - 27.0	.9998E+00	.9999E+00	.1000E+01	.1000E+01
27.0 - 30.0	.9999E+00	.1000E+01	.1000E+01	.1000E+01

Table A-15a

Mean Estimates of Breakage Probabilities

for Predamaged Plaster

MATERIAL TYPE = PLASTER

CONDITION = PREDAMAGED

CATEGORY = A

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressuer Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1921E-03	.2258E-02	.4504E-02	.7587E-02
2.5 - 4.0	.2156E-01	.9483E-01	.1393E+00	.1840E+00
4.0 - 6.0	.8436E-01	.2529E+00	.3309E+00	.3998E+00
6.0 - 8.0	.1933E+00	.4386E+00	.5292E+00	.6013E+00
8.0 - 10.0	.3119E+00	.5873E+00	.6731E+00	.7363E+00
10.0 - 12.0	.4240E+00	.6982E+00	.7726E+00	.8240E+00
12.0 - 15.0	.5430E+00	.7936E+00	.8524E+00	.8907E+00
15.0 - 18.0	.6577E+00	.8680E+00	.9107E+00	.9368E+00
18.0 - 21.0	.7434E+00	.9139E+00	.9444E+00	.9622E+00
21.0 - 24.0	.8068E+00	.9426E+00	.9645E+00	.9766E+00
24.0 - 27.0	.8535E+00	.9610E+00	.9767E+00	.9851E+00
27.0 - 30.0	.8879E+00	.9730E+00	.9844E+00	.9903E+00

Table A-15b

Mean Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER
CONDITION = PREDAMAGED
CATEGORY = B
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.3343E-04	.9618E-04	.1804E-03	.2714E-03
2.5 - 4.0	.6762E-02	.1351E-01	.2021E-01	.2613E-01
4.0 - 6.0	.3379E-01	.5828E-01	.7961E-01	.9694E-01
6.0 - 8.0	.9331E-01	.1441E+00	.1839E+00	.2142E+00
8.0 - 10.0	.1716E+00	.2452E+00	.2988E+00	.3375E+00
10.0 - 12.0	.2574E+00	.3472E+00	.4086E+00	.4512E+00
12.0 - 15.0	.3618E+00	.4621E+00	.5265E+00	.5694E+00
15.0 - 18.0	.4771E+00	.5796E+00	.6415E+00	.6812E+00
18.0 - 21.0	.5748E+00	.6726E+00	.7286E+00	.7634E+00
21.0 - 24.0	.6551E+00	.7446E+00	.7937E+00	.8233E+00
24.0 - 27.0	.7202E+00	.8000E+00	.8422E+00	.8669E+00
27.0 - 30.0	.7723E+00	.8425E+00	.8783E+00	.8988E+00

Table A-15c

Mean Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER
CONDITION = PREDAMAGED
CATEGORY = C
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1535E-04	.5137E-04	.1121E-03	.1832E-03
2.5 - 4.0	.4521E-02	.1000E-01	.1650E-01	.2247E-01
4.0 - 6.0	.2549E-01	.4772E-01	.7033E-01	.8908E-01
6.0 - 8.0	.7621E-01	.1257E+00	.1704E+00	.2045E+00
8.0 - 10.0	.1472E+00	.2224E+00	.2843E+00	.3288E+00
10.0 - 12.0	.2285E+00	.3229E+00	.3953E+00	.4448E+00
12.0 - 15.0	.3305E+00	.4388E+00	.5159E+00	.5662E+00
15.0 - 18.0	.4465E+00	.5595E+00	.6345E+00	.6811E+00
18.0 - 21.0	.5470E+00	.6563E+00	.7246E+00	.7653E+00
21.0 - 24.0	.6310E+00	.7319E+00	.7918E+00	.8263E+00
24.0 - 27.0	.6996E+00	.7904E+00	.8417E+00	.8705E+00
27.0 - 30.0	.7551E+00	.8352E+00	.8788E+00	.9025E+00

Table A-15d

Mean Estimates of Breakage Probabilities

for Predamaged Plaster

MATERIAL TYPE = PLASTER

CONDITION = PREDAMAGED

CATEGORY = D

WAVE TYPE = FOCUSED WAVE

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressuer Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.5821E-03	.1633E-02	.2853E-02	.4571E-02
2.5 - 4.0	.4603E-01	.8401E-01	.1148E+00	.1483E+00
4.0 - 6.0	.1530E+00	.2365E+00	.2945E+00	.3509E+00
6.0 - 8.0	.3081E+00	.4226E+00	.4928E+00	.5555E+00
8.0 - 10.0	.4532E+00	.5747E+00	.6427E+00	.6996E+00
10.0 - 12.0	.5746E+00	.6894E+00	.7490E+00	.7964E+00
12.0 - 15.0	.6895E+00	.7883E+00	.8359E+00	.8719E+00
15.0 - 18.0	.7880E+00	.8655E+00	.9002E+00	.9251E+00
18.0 - 21.0	.8538E+00	.9129E+00	.9378E+00	.9548E+00
21.0 - 24.0	.8979E+00	.9425E+00	.9602E+00	.9720E+00
24.0 - 27.0	.9278E+00	.9613E+00	.9740E+00	.9821E+00
27.0 - 30.0	.9482E+00	.9734E+00	.9826E+00	.9883E+00

Table A-16a

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER
CONDITION = PREDAMAGED
CATEGORY = A
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.3247E-02	.2074E-01	.3501E-01	.5173E-01
2.5 - 4.0	.7816E-01	.2280E+00	.3019E+00	.3686E+00
4.0 - 6.0	.2184E+00	.4578E+00	.5480E+00	.6194E+00
6.0 - 8.0	.3912E+00	.6535E+00	.7327E+00	.7895E+00
8.0 - 10.0	.5379E+00	.7781E+00	.8395E+00	.8801E+00
10.0 - 12.0	.6525E+00	.8560E+00	.9013E+00	.9295E+00
12.0 - 15.0	.7560E+00	.9138E+00	.9442E+00	.9620E+00
15.0 - 18.0	.8389E+00	.9516E+00	.9704E+00	.9808E+00
18.0 - 21.0	.8919E+00	.9717E+00	.9836E+00	.9897E+00
21.0 - 24.0	.9262E+00	.9829E+00	.9905E+00	.9943E+00
24.0 - 27.0	.9487E+00	.9894E+00	.9943E+00	.9967E+00
27.0 - 30.0	.9638E+00	.9932E+00	.9965E+00	.9980E+00

Table A-16b

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER
CONDITION = PREDAMAGED
CATEGORY = B
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1646E-02	.3538E-02	.5682E-02	.7680E-02
2.5 - 4.0	.5646E-01	.8983E-01	.1190E+00	.1417E+00
4.0 - 6.0	.1717E+00	.2406E+00	.2938E+00	.3318E+00
6.0 - 8.0	.3275E+00	.4194E+00	.4835E+00	.5262E+00
8.0 - 10.0	.4695E+00	.5662E+00	.6288E+00	.6685E+00
10.0 - 12.0	.5866E+00	.6780E+00	.7337E+00	.7677E+00
12.0 - 15.0	.6977E+00	.7767E+00	.8220E+00	.8486E+00
15.0 - 18.0	.7918E+00	.8545E+00	.8883E+00	.9074E+00
18.0 - 21.0	.8550E+00	.9034E+00	.9283E+00	.9418E+00
21.0 - 24.0	.8976E+00	.9346E+00	.9529E+00	.9625E+00
24.0 - 27.0	.9267E+00	.9550E+00	.9684E+00	.9753E+00
27.0 - 30.0	.9468E+00	.9684E+00	.9783E+00	.9833E+00

Table A-16c

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER
CONDITION = PREDAMAGED
CATEGORY = C
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.7891E-03	.1915E-02	.3486E-02	.5058E-02
2.5 - 4.0	.3722E-01	.6431E-01	.9244E-01	.1151E+00
4.0 - 6.0	.1293E+00	.1934E+00	.2508E+00	.2926E+00
6.0 - 8.0	.2689E+00	.3623E+00	.4370E+00	.4871E+00
8.0 - 10.0	.4065E+00	.5109E+00	.5875E+00	.6358E+00
10.0 - 12.0	.5265E+00	.6295E+00	.6999E+00	.7423E+00
12.0 - 15.0	.6456E+00	.7381E+00	.7971E+00	.8308E+00
15.0 - 18.0	.7505E+00	.8264E+00	.8715E+00	.8961E+00
18.0 - 21.0	.8233E+00	.8833E+00	.9170E+00	.9347E+00
21.0 - 24.0	.8736E+00	.9204E+00	.9453E+00	.9579E+00
24.0 - 27.0	.9086E+00	.9448E+00	.9633E+00	.9723E+00
27.0 - 30.0	.9331E+00	.9611E+00	.9748E+00	.9814E+00

Table A-16d

Mean Plus One Sigma Estimates of Breakage Probabilities for Predamaged Plaster

MATERIAL TYPE = PLASTER
CONDITION = PREDAMAGED
CATEGORY = D
WAVE TYPE = FOCUSED WAVE
LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Wave Duration (sec) 0.05 - 0.10	0.10 - 0.15	0.15 - 0.25	0.25 - 0.35
0.5 - 2.5	.1237E-01	.2514E-01	.3750E-01	.5225E-01
2.5 - 4.0	.1929E+00	.2798E+00	.3422E+00	.4015E+00
4.0 - 6.0	.4164E+00	.5289E+00	.5986E+00	.6578E+00
6.0 - 8.0	.6195E+00	.7216E+00	.7777E+00	.8216E+00
8.0 - 10.0	.7533E+00	.8335E+00	.8740E+00	.9036E+00
10.0 - 12.0	.8387E+00	.8984E+00	.9264E+00	.9459E+00
12.0 - 15.0	.9027E+00	.9430E+00	.9606E+00	.9722E+00
15.0 - 18.0	.9453E+00	.9702E+00	.9803E+00	.9867E+00
18.0 - 21.0	.9681E+00	.9837E+00	.9897E+00	.9933E+00
21.0 - 24.0	.9808E+00	.9907E+00	.9943E+00	.9964E+00
24.0 - 27.0	.9881E+00	.9945E+00	.9967E+00	.9980E+00
27.0 - 30.0	.9924E+00	.9966E+00	.9981E+00	.9988E+00

Table A-17a

Mean Estimates of Breakage Probabilities for Bric-a-Brac

MATERIAL TYPE = BRIC-A-BRAC

LEVEL OF CONSERVATISM = MEAN + .00 SIGMA

Over Pressure Range (psf)	Breakage Probability
0.5 - 2.5	.8908E-10
2.5 - 4.0	.4673E-07
4.0 - 6.0	.4814E-06
6.0 - 8.0	.2663E-05
8.0 - 10.0	.8692E-05
10.0 - 12.0	.2132E-04
12.0 - 15.0	.5039E-04
15.0 - 18.0	.1140E-03
18.0 - 21.0	.2182E-03
21.0 - 24.0	.3723E-03
24.0 - 27.0	.5843E-03
27.0 - 30.0	.8601E-03

Table A-17b

Mean Plus One Sigma Estimates of Breakage Probabilities for Bric-a-Brac

MATERIAL TYPE = BRIC-A-BRAC

LEVEL OF CONSERVATISM = MEAN + 1.00 SIGMA

Over Pressure Range (psf)	Breakage Probability
0.5 - 2.5	.1636E-06
2.5 - 4.0	.1840E-04
4.0 - 6.0	.1129E-03
6.0 - 8.0	.4148E-03
8.0 - 10.0	.1007E-02
10.0 - 12.0	.1956E-02
12.0 - 15.0	.3673E-02
15.0 - 18.0	.6603E-02
18.0 - 21.0	.1045E-01
21.0 - 24.0	.1518E-01
24.0 - 27.0	.2071E-01
27.0 - 30.0	.2695E-01

APPENDIX B

CONTRIBUTIONS TO DAF UNCERTAINTY

Table B-1 Uncertainty in Window Log (DAF) from Duration Uncertainty for N-Waves

Duration Interval (sec)	Variance (Log (DAF))				
	Window Category				
	A	B	C	D	E
0.05 - 0.10	1.5×10^{-5}	3.4×10^{-5}	8.1×10^{-4}	6.3×10^{-3}	8.4×10^{-3}
0.10 - 0.15	1.7×10^{-6}	4.2×10^{-6}	1.2×10^{-4}	3.7×10^{-4}	1.9×10^{-3}
0.15 - 0.25	1.1×10^{-6}	2.7×10^{-6}	3.0×10^{-5}	8.1×10^{-4}	3.7×10^{-4}
0.25 - 0.35	1.8×10^{-7}	4.8×10^{-7}	5.5×10^{-6}	3.7×10^{-4}	5.9×10^{-4}

Table B-2 Uncertainty in Window Log (DAF) from Duration Uncertainty for N-Waves

Duration Interval (sec)	Variance (Log (DAF))				
	Window Category				
	A	B	C	D	E
0.05 - 0.10	1.7×10^{-3}	2.3×10^{-3}	2.8×10^{-3}	5.2×10^{-3}	2.1×10^{-3}
0.10 - 0.15	4.1×10^{-4}	4.8×10^{-4}	8.0×10^{-4}	1.4×10^{-3}	9.1×10^{-3}
0.15 - 0.25	2.3×10^{-4}	4.6×10^{-4}	9.4×10^{-4}	2.1×10^{-4}	2.0×10^{-3}
0.25 - 0.35	3.0×10^{-5}	3.7×10^{-4}	1.6×10^{-3}	1.3×10^{-3}	5.2×10^{-4}

Table B-3 Uncertainty in Window Log(DAF) from Natural Frequency Uncertainty for N-waves

Window Category	Uncertainty
A	5.45×10^{-5}
B	7.88×10^{-4}
C	7.42×10^{-3}
D	1.58×10^{-2}
E	0.1926

Table B-4 Uncertainty in Window Log(DAF) from Natural Frequency Uncertainty for Focused Waves

Window Category	Uncertainty
A	1.41×10^{-3}
B	4.26×10^{-3}
C	4.64×10^{-2}
D	3.23×10^{-2}
E	4.45×10^{-2}

Table B-5 Uncertainty in Plaster Log(DAF) from Duration Uncertainty for N-Waves

Duration Interval (sec)	Variance (Log (DAF))			
	Plaster Category			
	A	B	C	D
0.05 - 0.10	7.5×10^{-4}	1.7×10^{-4}	2.7×10^{-4}	2.8×10^{-4}
0.10 - 0.15	1.6×10^{-4}	1.6×10^{-5}	2.1×10^{-5}	2.5×10^{-5}
0.15 - 0.25	3.9×10^{-5}	1.0×10^{-5}	1.3×10^{-5}	1.6×10^{-5}
0.25 - 0.35	6.8×10^{-6}	1.8×10^{-6}	2.4×10^{-6}	2.8×10^{-6}

Table B-6. Uncertainty in Plaster Log (DAF) from Duration Uncertainty for Focused Waves

Duration Interval (sec)	Variance (Log (DAF))			
	Plaster Category			
	A	B	C	D
0.05 - 0.10	4.61×10^{-3}	2.61×10^{-3}	3.11×10^{-3}	3.41×10^{-3}
0.10 - 0.15	6.47×10^{-4}	2.97×10^{-4}	3.88×10^{-4}	4.31×10^{-4}
0.15 - 0.25	5.04×10^{-4}	3.40×10^{-4}	3.42×10^{-4}	3.94×10^{-4}
0.25 - 0.35	4.95×10^{-4}	1.61×10^{-4}	2.45×10^{-4}	3.13×10^{-4}

Table B-7 Uncertainty in Plaster Log(DAF) from Natural Frequency Uncertainty for N-Waves

Plaster Category	Uncertainty
A	2.46×10^{-3}
B	2.78×10^{-5}
C	2.85×10^{-4}
D	2.70×10^{-5}

Table B-8 Uncertainty in Plaster Log(DAF) from Natural Frequency Uncertainty for Focused Waves

Plaster Category	Uncertainty
A	1.24×10^{-2}
B	1.74×10^{-2}
C	4.12×10^{-3}
D	2.80×10^{-3}

Table B-9 Log(DAF) Statistics for ASAN Damage Model

Table B-9a Window Log(DAF) Statistics for N-Waves

Category A

Duration Interval (sec)	Mean Log DAF	Variance Log DAF Total	Variance Log DAF Damping	Variance Log DAF Wave Shape
0.05 - 0.10	0.2524	1.33×10^{-3}	2.0×10^{-5}	1.3×10^{-3}
0.10 - 0.15	0.2679	1.33×10^{-3}	2.0×10^{-5}	1.3×10^{-3}
0.15 - 0.25	0.2749	1.33×10^{-3}	2.0×10^{-5}	1.3×10^{-3}
0.25 - 0.35	0.2795	1.33×10^{-3}	2.0×10^{-5}	1.3×10^{-3}

Category B

Duration Interval (sec)	Mean Log DAF	Variance Log DAF Total	Variance Log DAF Damping	Variance Log DAF Wave Shape
0.05 - 0.10	0.2324	2.77×10^{-3}	2.8×10^{-4}	2.5×10^{-3}
0.10 - 0.15	0.2558	2.77×10^{-3}	2.8×10^{-4}	2.5×10^{-3}
0.15 - 0.25	0.2670	2.77×10^{-3}	2.8×10^{-4}	2.5×10^{-3}
0.25 - 0.35	0.2739	$2\ 77 \times 10^{-3}$	2.8×10^{-4}	2.5×10^{-3}

Table B-9a Window Log(DAF) Statistics for N-Waves

Category C

Duration Interval (sec)	Mean Log DAF	Variance Log DAF Total	Damping	Wave Shape
0.05 - 0.10	0.2099	8.37×10^{-3}	2.9×10^{-4}	8.1×10^{-3}
0.10 - 0.15	0.2185	8.37×10^{-3}	2.9×10^{-4}	8.1×10^{-3}
0.15 - 0.25	0.2183	8.37×10^{-3}	2.9×10^{-4}	8.1×10^{-3}
0.25 - 0.35	0.2418	8.37×10^{-3}	2.9×10^{-4}	8.1×10^{-3}

Category D

Duration Interval (sec)	Mean Log DAF	Variance Log DAF Total	Damping	Wave Shape
0.05 - 0.10	-0.0603	1.35×10^{-2}	8.1×10^{-5}	1.3×10^{-2}
0.10 - 0.15	0.2362	1.35×10^{-2}	8.1×10^{-5}	1.3×10^{-2}
0.15 - 0.25	0.2073	1.35×10^{-2}	8.1×10^{-5}	1.3×10^{-2}
0.25 - 0.35	0.1897	1.35×10^{-2}	8.1×10^{-5}	1.3×10^{-2}

Table B-9a Window Log (DAF) Statistics for N-Waves

Category E				
Duration Interval (sec)	Mean Log DAF	Variance Log DAF		
		Total	Damping	Wave Shape
0.05 - 0.10	-0.3605	2.36×10^{-2}	8.1×10^{-5}	2.3×10^{-2}
0.10 - 0.15	0.0436	2.36×10^{-2}	8.1×10^{-5}	2.3×10^{-2}
0.15 - 0.25	0.2312	2.36×10^{-2}	8.1×10^{-5}	2.3×10^{-2}
0.25 - 0.35	0.1899	2.36×10^{-2}	8.1×10^{-5}	2.3×10^{-2}

Table B-9b Window Log(DAF) Statistics for Focused Waves

Category A

Duration Interval (sec)	Mean Log DAF	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	0.1529	9.91×10^{-3}	2.26×10^{-3}	6.93×10^{-3}
0.10 - 0.15	0.1695	9.91×10^{-3}	2.26×10^{-3}	6.93×10^{-3}
0.15 - 0.25	0.1264	9.91×10^{-3}	2.26×10^{-3}	6.93×10^{-3}
0.25 - 0.35	0.0951	9.91×10^{-3}	2.26×10^{-3}	6.93×10^{-3}

Category B

Duration Interval (sec)	Mean Log DAF	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	0.1211	9.36×10^{-3}	1.55×10^{-3}	7.81×10^{-3}
0.10 - 0.15	0.1760	9.36×10^{-3}	1.55×10^{-3}	7.81×10^{-3}
0.15 - 0.25	0.1711	9.36×10^{-3}	1.55×10^{-3}	7.81×10^{-3}
0.25 - 0.35	0.1195	9.36×10^{-3}	1.55×10^{-3}	7.81×10^{-3}

Table B-9b Window Log(DAF) Statistics for Focused Waves

Category C

Duration Interval (sec)	Mean Log DAF	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	-0.0333	1.10×10^{-2}	4.59×10^{-4}	1.05×10^{-2}
0.10 - 0.15	0.0582	1.10×10^{-2}	4.59×10^{-4}	1.05×10^{-2}
0.15 - 0.25	0.0914	1.10×10^{-2}	4.59×10^{-4}	1.05×10^{-2}
0.25 - 0.35	0.1422	1.10×10^{-2}	4.59×10^{-4}	1.05×10^{-2}

Category D

Duration Interval (sec)	Mean Log DAF	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	-0.4674	2.78×10^{-2}	3.25×10^{-4}	2.75×10^{-2}
0.10 - 0.15	-0.2596	2.78×10^{-2}	3.25×10^{-4}	2.75×10^{-2}
0.15 - 0.25	-0.1130	2.78×10^{-2}	3.25×10^{-4}	2.75×10^{-2}
0.25 - 0.35	-0.0092	2.78×10^{-2}	3.25×10^{-4}	2.75×10^{-2}

Table B-9b Window Log (DAF) Statistics for Focused Waves

Category E				
Duration Interval (sec)	Mean Log DAF	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	-0.5925	2.82×10^{-2}	3.36×10^{-4}	2.79×10^{-2}
0.10 - 0.15	-0.4142	2.82×10^{-2}	3.36×10^{-4}	2.79×10^{-2}
0.15 - 0.25	-0.2367	2.82×10^{-2}	3.36×10^{-4}	2.79×10^{-2}
0.25 - 0.35	-0.1148	2.82×10^{-2}	3.36×10^{-4}	2.79×10^{-2}

Table B-9c <u>Plaster Log (DAF) Statistics for N-Waves</u>

Category A -- Ceiling

Duration Interval (sec)	Mean Log DAF	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	0.1896	$7.06x10^{-3}$	$1.8x10^{-4}$	$6.9x10^{-3}$
0.10 - 0.15	0.1691	$7.06x10^{-3}$	$1.8x10^{-4}$	$6.9x10^{-3}$
0.15 - 0.25	0.1973	$7.06x10^{-3}$	$1.8x10^{-4}$	$6.9x10^{-3}$
0.25 - 0.35	0.2238	$7.06x10^{-3}$	$1.8x10^{-4}$	$6.9x10^{-3}$

Category B -- Wood Stud Wall

Duration Interval (sec)	Mean Log DAF	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	0.1691	$2.36x10^{-3}$	$1.8x10^{-4}$	$2.2x10^{-3}$
0.10 - 0.15	0.2139	$2.36x10^{-3}$	$1.8x10^{-4}$	$2.2x10^{-3}$
0.15 - 0.25	0.2356	$2.36x10^{-3}$	$1.8x10^{-4}$	$2.2x10^{-3}$
0.25 - 0.35	0.2492	$2.36x10^{-3}$	$1.8x10^{-4}$	$2.2x10^{-3}$

Table B-9c Plaster Log(DAF) Statistics for N-Waves

Category C -- Brick Wall

Duration Interval (sec)	Mean (Log (DAF))	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	0.1586	3.12×10^{-3}	1.8×10^{-4}	2.9×10^{-3}
0.10 - 0.15	0.2047	3.12×10^{-3}	1.8×10^{-4}	2.9×10^{-3}
0.15 - 0.25	0.2294	3.12×10^{-3}	1.8×10^{-4}	2.9×10^{-3}
0.25 - 0.35	0.2452	3.12×10^{-3}	1.8×10^{-4}	2.9×10^{-3}

Category D -- Partition Wall

Duration Interval (sec)	Mean (Log (DAF))	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	0.1584	3.50×10^{-3}	1.8×10^{-4}	3.3×10^{-3}
0.10 - 0.15	0.1991	3.50×10^{-3}	1.8×10^{-4}	3.3×10^{-3}
0.15 - 0.25	0.2259	3.50×10^{-3}	1.8×10^{-4}	3.3×10^{-3}
0.25 - 0.35	0.2428	3.50×10^{-3}	1.8×10^{-4}	3.3×10^{-3}

Table B-9d Plaster Log(DAF) Statistics for Focused Waves

Category A -- Ceiling

Duration Interval (sec)	Mean (Log (DAF))	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	-0.2400	9.90×10^{-3}	3.02×10^{-3}	6.88×10^{-3}
0.10 - 0.15	-0.0304	9.90×10^{-3}	3.02×10^{-3}	6.88×10^{-3}
0.15 - 0.25	0.0368	9.90×10^{-3}	3.02×10^{-3}	6.88×10^{-3}
0.25 - 0.35	0.0909	9.90×10^{-3}	3.02×10^{-3}	6.88×10^{-3}

Category B -- Wood Stud Wall

Duration Interval (sec)	Mean (Log (DAF))	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	-0.0126	1.11×10^{-2}	4.99×10^{-3}	6.12×10^{-3}
0.10 - 0.15	0.0641	1.11×10^{-2}	4.99×10^{-3}	6.12×10^{-3}
0.15 - 0.25	0.1121	1.11×10^{-2}	4.99×10^{-3}	6.12×10^{-3}
0.25 - 0.35	0.1443	1.11×10^{-2}	4.99×10^{-3}	6.12×10^{-3}

Table B-9d Plaster Log(DAF) Statistics for Focused Waves

Category C -- Brick Wall

Duration Interval (sec)	Mean (Log (DAF))	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	-0.0344	6.61×10^{-3}	5.19×10^{-4}	6.09×10^{-3}
0.10 - 0.15	0.0478	6.61×10^{-3}	5.19×10^{-4}	6.09×10^{-3}
0.15 - 0.25	0.1039	6.61×10^{-3}	5.19×10^{-4}	6.09×10^{-3}
0.25 - 0.35	0.1400	6.61×10^{-3}	5.19×10^{-4}	6.09×10^{-3}

Category D -- Partition Wall

Duration Interval (sec)	Mean (Log (DAF))	Variance (Log (DAF)) Total	Damping	Wave Shape
0.05 - 0.10	-0.0481	6.07×10^{-3}	4.86×10^{-4}	6.02×10^{-3}
0.10 - 0.15	0.0401	6.07×10^{-3}	4.86×10^{-4}	6.02×10^{-3}
0.15 - 0.25	0.0912	6.07×10^{-3}	4.86×10^{-4}	6.02×10^{-3}
0.25 - 0.35	0.1366	6.07×10^{-3}	4.86×10^{-4}	6.02×10^{-3}

APPENDIX C

THE EFFECTS OF SONIC BOOMS ON CONVENTIONAL STRUCTURES

Sonic boom damage to conventional structures is a function of the applied load and the building elements' capacities. The incoming sonic boom wave produces an applied load to a building element. The response of that element depends upon the characteristics of the element and the time history of the applied load. When the dynamic response of the element exceeds its capacity, damage occurs.

A supersonic overflight generates a sonic boom. The ground level overpressures are affected by the size of the aircraft, the aircraft speed, and the aircraft altitude. Overpressures increase with aircraft weight and size and decrease with the distance the sonic boom travels to reach the ground. The effect of aircraft speed on overpressures is less pronounced. At low supersonic speeds overpressures increase with increased speed. At higher speeds, the overpressures decrease with increased speed. Sonic boom durations are proportional to the aircraft length and the distance from the aircraft to the observer.

Under most conditions the sonic boom wave at ground level has a time history that is approximately "N-shaped". Local atmospheric conditions frequently will produce variations on the basic N-wave which are more "spikey" or more rounded. Larger scale atmospheric variations change both the amplitude and duration of the sonic boom wave. Sonic boom waves generated by aircraft flying just slightly in excess of the speed of sound are particularly susceptible to these effects. Extreme variations of the atmosphere can produce a local focusing of the sonic boom in a "U-shaped" wave. Acceleration of an aircraft (turning, pitchover maneuvers, or linear acceleration) also

produces enhanced overpressures and, in a localized region, focused U-waves.

Near the edges of the sonic boom carpet the waves change from an N-wave to a more rounded wave (similar to a sine wave). In this region there is a large scatter in the wave shapes and overpressure amplitudes because of the direction of propagation of the wave.

Typical supersonic fighter sorties generate maximum overpressures between 1 and 5 pounds per square foot (psf). Extreme focal overpressures from typical maneuver altitudes are less than 20 psf. Durations for fighter sonic booms are typically from 50 to 150 ms, while for bombers they can be as long as 300 ms.

The approaching sonic boom wave may strike a building element directly or reach that element only after being reflected from another surface. The wave reaching portions of the back of a building is also affected by diffraction as the wave passes over the building. The applied external load will be some combination of these waves. The effective net load that a building element sees is the difference between the external load in front of the element and the load on the back of the element. (Depending on the type of structural response being considered, the back of the element may be the inside of the building or the far side of the building. The short duration and relatively small overpressures of sonic booms allow the response of a building element to be reasonably described without considering the rest of the structure. That is, the rest of the building may modify the applied load, but not the element response.)

At low overpressure levels, the dynamic response of the building element can relieve stresses accumulated in the element from natural environmental forces which act slowly over a long period of time. For example, temperature, humidity, and settlement can cause stresses to develop between dissimilar materials like plaster, nails, wood, and stucco. Low overpressure sonic booms can induce just enough motion in the building element to overcome the friction between the materials, allow the materials to rearrange slightly and thus relieve some of the preexisting stress. As a result, the low overpressure booms can slow down the deterioration of the building from naturally occurring forces.

Definition of the capacity of an element involves additional complicating factors. In the United States of America the greatest number of sonic boom damage incidents has been to glass, plaster and bric-a-brac (in that order). Assessing the capacity of each of these elements poses special problems.

The glass industry has performed extensive testing to assess the capacity of new panes. However, as soon as glass leaves the factory it is subjected to abuse during handling which generates surface flaws. During and after installation, glazier's points may scratch or abrade the window. Distortion of the frame may introduce additional patterns of stress in the glass. Glass breakage is highly correlated with the location and severity of these flaws and stress raisers. Appropriate characterization of the resulting reduced capacity of windows is a complex problem.

Plaster differs from glass in several important ways. Plaster is virtually never used by itself in construction; it is always used in conjunction with some type of backing material. In addition, the combination of gypsum, aggregate, and water used in their mixtures varies from plasterer to plasterer. The proportion of ingredients, the completeness of mixing, and the

removal of air bubbles depend on the workmanship of the plasterer. A critical characteristic of the mixture is the proper ratio of water to plaster. Use of either too little or too much water will weaken the resultant product. Similarly, achieving the proper bonding of the plaster coating to the backing and the intended plaster thickness varies with workmanship. So, there is a large variation in the capacity of plaster elements.

Bric-a-brac, miscellaneous articles which sit on surfaces such as shelves or tables, is the most ill-defined of these categories. This category includes objects ranging from the stable, well placed, sturdy items -- such as a steel disc paperweight in the middle of a desk -- to the fragile, precariously placed, unstable objects -- such as a tall china vase sitting on the edge of a shelf above a concrete floor. Obviously, the range of types of objects considered to be bric-a-brac and conditions in which they may be found is enormous.

The uncertainties in the net applied sonic boom load and in building element capacities are large. Consequently, anticipated damages must be assessed probabilistically. Such a model evaluates the probability that the applied load exceeds the capacity of a building element.

Sources of load and capacity variability are grouped into two categories. Variations in the capacity or the load which are created by categorization or underspecifying the problem fall into one category. This category results in systematic shifting of damage estimates. The effect of these variations is uncertainty in damage estimates. Variations which remain after the scenario is well specified are random in nature. The extent by which the random variations in load exceed the random variations in capacity is the probability of damage. Samples of

curves of the probability of damage as a function of over pressure are shown in Figures C-1 through C-3.

Standard planning categories (e.g., single family dwelling, multi-family dwelling with 10 units, school with 10 classrooms, etc.) are used to describe the structures at risk. The model associates with each building estimates (means and variances) of the number of windows, plaster walls and ceilings, and pieces of bric-a-brac. The location of the structures are mapped with respect to the sonic boom footprint expected from the supersonic operations being evaluated.

Associated with each location is the frequency with which it will be subjected to each type of sonic boom wave (focused and N-waves), peak overpressure and duration. The model evaluates the probability of damage to each combination of building element, location, and loading condition. Means and variances of the number of damaged windows, ceilings, walls and pieces of bric-a-brac are accumulated and reported for each planning category as well as a grand total of damage anticipated from a planned set of supersonic operations.

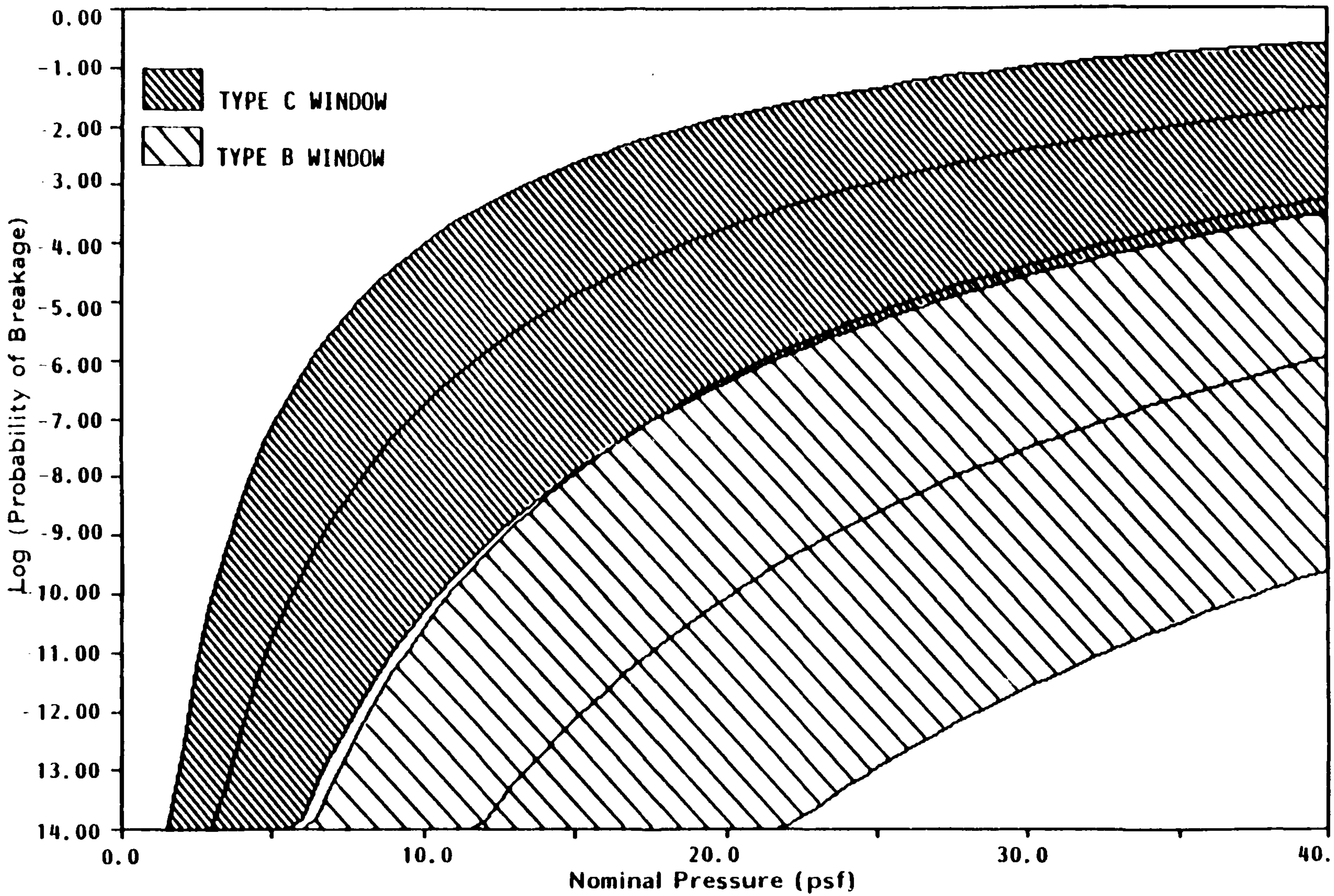

Figure C-1. Probability of Breakage for Type B and C Windows (Mean ± One Standard Deviation Bounds)

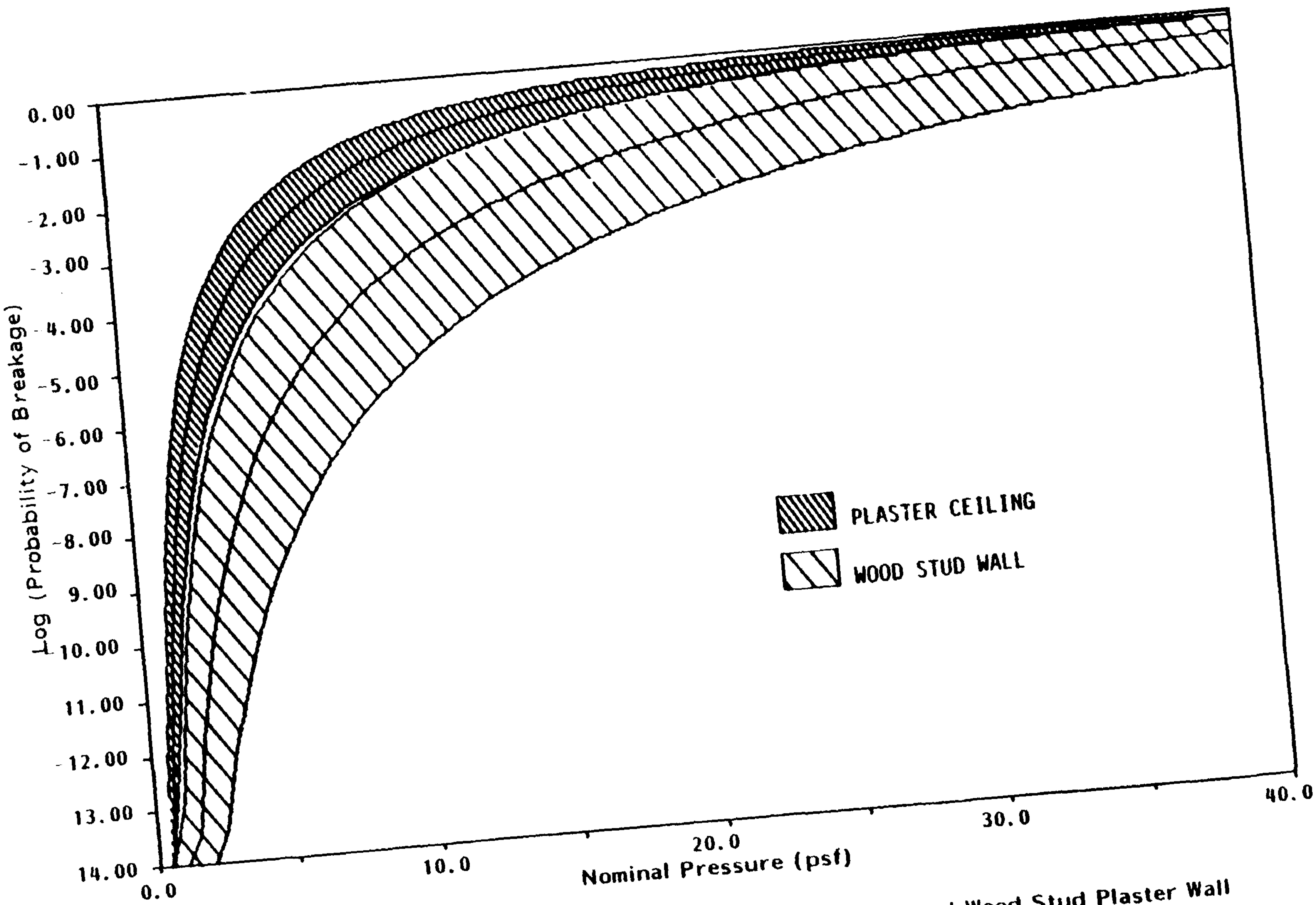

Figure C-2. Probability of Breakage for Plaster Ceiling and Wood Stud Plaster Wall (Mean ± One Standard Deviation Bounds)

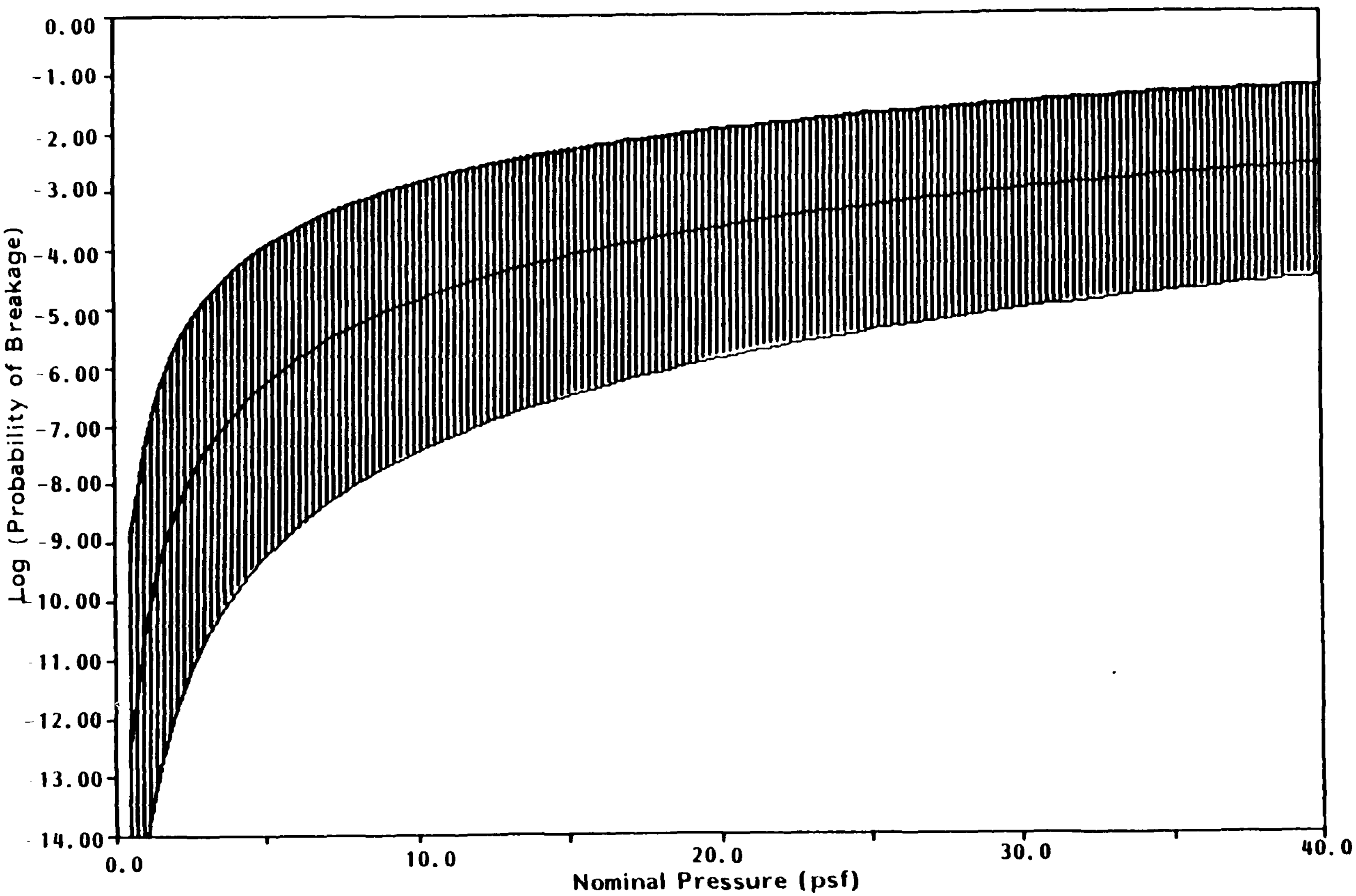

Figure C-3. Probability of Breakage for Bric-a-brac (Mean ± One Standard Deviation Bounds)

APPENDIX D

A S A N PROTOTYPE
CONVENTIONAL STRUCTURES
DAMAGE ASSESSMENT SCREENS

SCREEN 1

A S A N PLANNING CATEGORIES ARE SHOWN BELOW

SINGLE FAMILY DWELLINGS
MOBILE HOMES
MULTIFAMILY DWELLINGS
SCHOOLS
CHURCHES
HOSPITALS
OFFICE BUILDINGS
COMMERCIAL BUILDINGS

Do you wish to add a planning category for this evaluation?

Y E S	(SWITCH TO SCREEN 2)
N O	(SWITCH TO SCREEN 4)

SCREEN 2

DEFINITION OF NEW PLANNING CATEGORY

ENTER NAME OF CATEGORY

DO YOU WISH TO ENTER A PARAMETER (E.G. NUMBER OF OFFICES) TO DEFINE SUBCATEGORIES?

Y E S
N O

(IF YES)

ENTER PARAMETER NAME (N)

(SWITCH TO SCREEN 3)

SCREEN 3

YOU WILL NOW DEFINE THE NEW PLANNING CATEGORY IN TERMS OF VULNERABLE ELEMENTS. MOVE THE CURSOR THROUGH THE TABLE AND PLACE AN ENTRY IN EACH POSITION (PRESS F-1 FOR HELP SCREEN)

NUMBER OF WINDOWS

	BEST ESTIMATE	VARIANCE
TYPE A	______ + ______ N	(______ + ______ N)^2
TYPE B	______ + ______ N	(______ + ______ N)^2
TYPE C	______ + ______ N	(______ + ______ N)^2
TYPE D	______ + ______ N	(______ + ______ N)^2
TYPE E	______ + ______ N	(______ + ______ N)^2

ENTER F-10 WHEN COMPLETE

(ASAN TO ASSURE ALL BLANKS ARE FILLED; WHEN FILLED STORE DATA AND CHANGE WINDOW DISPLAY TO PLASTER SHOWN BELOW)

NUMBER OF PLASTER ELEMENTS

	BEST ESTIMATE	VARIANCE
TYPE A .. CEILING	___ + ___ N	$(\_\_\_\_ + \_\_\_\_ N)^2$
TYPE B .. WALL	___ + ___ N	$(\_\_\_\_ + \_\_\_\_ N)^2$
TYPE C .. WALL	___ + ___ N	$(\_\_\_\_ + \_\_\_\_ N)^2$
TYPE D .. WALL	___ + ___ N	$(\_\_\_\_ + \_\_\_\_ N)^2$

(ASAN TO ASSURE ALL BLANK FILLED; WHEN FILLED, STORE DATA AND DISPLAY)

DO YOU WISH TO DEFINE ANYMORE CATEGORIES?

Y E S	(SWITCH TO SCREEN 2)
N O	(SWITCH TO SCREEN 4)

HELPSCREEN FOR SCREEN 3

THE WINDOW TYPES ARE DEFINED BY AREA:

TYPE	AREA (SQUARE FEET)
A	0-2
B	2-10
C	10-50
D	50-100
E	>100

PLASTER ELEMENT TYPES ARE:

TYPE	DESCRIPTION
A	WOOD FRAMED CEILING
B	WOOD FRAME WALL
C	BRICK MASONRY WALL
D	METAL; STUD PARTITION WALL

IF YOU ARE DESCRIBING THE NUMBER OF ELEMENTS IN A CATEGORY, YOU CAN ESTIMATE ITS VARIANCE AS FOLLOWS:

1. ESTIMATE THE LARGEST AND SMALLEST NUMBER OF ELEMENTS

2. DIVIDE THE DIFFERENCE BETWEEN THE TWO BY SIX

3. SQUARE THE RESULT

(TYPE ESCAPE TO RETURN TO THE PREVIOUS SCREEN)

SCREEN 4

INDICATE ON THE SCREEN DISPLAYING THE PLANNING MAP THE LOCATION OF THE NEXT FACILITY TO ENTER. DEPRESS ENTER WHEN READY.

USE ARROWS TO MOVE CURSOR UP OR DOWN. SELECT TO ELECT PLANNING CATEGORY.

SINGLE FAMILY DWELLINGS

MOBILE HOMES

MULTI FAMILY DWELLINGS

SCHOOLS

CHURCHES

COMMERCIAL BUILDINGS

OFFICE BUILDINGS

IF MOBILE HOMES IS SELECTED DISPLAY

ENTER TYPE OF EXTERIOR WALL   WOOD ______

METAL ______

IF MULTI-FAMILY DWELLING IS SELECTED DISPLAY

ENTER NUMBER OF UNITS ______

IF SCHOOLS IS SELECTED DISPLAY

ENTER NUMBER OF CLASSROOMS ______

IF HOSPITALS IS SELECTED DISPLAY

ENTER NUMBER OF BEDS ______

IF OFFICE BUILDINGS IS SELECTED DISPLAY

ENTER NUMBER OF FLOORS ______

DO YOU WISH TO ENTER ANOTHER FACILITY

YES _____ (MOVE CURSOR TO TOP)

NO _____ (SWITCH TO SCREEN 5)

SCREEN 5

DAMAGE ASSESSMENT REPORTING

PRODUCE TOTAL LOSS ESTIMATES BY MATERIAL TYPE _______

PRODUCE LOSS ESTIMATES BY MATERIAL TYPE AND
PLANNING CATEGORY _______

MOVE CURSOR TO REPORTING OPTIONS DESIRED AND DEPRESS RETURN TO SELECT/RESELECT OPTION. (SECTIONS WILL TOGGLE WITH REPEATED ENTRIES)